RSIC-607

ADHESION IN THE SPACE ENVIRONMENT

by

H. E. Pattee
R. E. Monroe

October 1966

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ABSTRACT

This report presents a comprehensive literature survey of adhesive bonding (cold welding) in the space environment. Space characteristics are summarized and experimental methods for reproducing these conditions are investigated. Information is particularly directed towards electronics and the metals used for electrical contacts. A total of 124 references are cited along with a selected bibliography of 44 citations.

FOREWORD

The purpose of this report is to present a state-of-the-art survey of the field of metal-to-metal adhesion or cold welding in the space environment. Included in this report is a discussion of the characteristics of the space environment and their effect on metals and metal surfaces, a review of the research on adhesion phenomena under atmospheric conditions and in an ultrahigh vacuum, and a discussion of the adhesion and friction experiments that have been or will be conducted under actual space conditions. This report was requested by R-QUAL-P, Marshall Space Flight Center, Huntsville, Alabama, under Contract No. DA-01-021-AMC-14693(Z).

The contents of this report are based on a search of the unclassified literature published since 1960. However, fundamental studies of adhesion, friction, wear, and lubrication were conducted long before this date by organizations concerned with the design and construction of equipment with moving parts. Although most of this research was conducted at atmospheric pressure, the results form the base for much of the technology of adhesion. Some of these data are included in this report; the literature under these subject headings should be consulted for more detailed information. The acquisition of data from Government-sponsored research was facilitated by searches of the literature in the files of the following agencies:

1) National Aeronautics and Space Administration.
2) Redstone Scientific Information Center.
3) Defense Documentation Center.

Other sources of information were the Defense Metals Information Center, other literature searches on subjects related to adhesion, and various engineering files.

In the case of Government-sponsored research, the results often appear in a paper or article in a technical journal as well as in a report to the sponsoring agency. Although the formal report is cited as the primary source of information, the articles are referenced also for those who do not have ready access to Government reports. Also, technical articles sometimes include discussion of the reported research.

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Section I. INTRODUCTION

The adhesion or cold welding of metals in the space environment is a source of concern to those engaged in space research. Metal-to-metal adhesion can occur under ultrahigh vacuum conditions when the surfaces of contacting metals are denuded of the oxides and films of adsorbed gases that are normally present under atmospheric conditions. Regardless of the manner in which these surface contaminants are removed, they will reform very slowly, if at all, in the hard vacuum of outer space. Provisions must be made prior to launch to minimize or prevent undesirable adhesion during a space mission.

Despite the current emphasis on the prevention of adhesion, the day is rapidly approaching when it may be desirable to use this process as a means to join metals in the space environment. The Marshall Space Flight Center (MSFC) is studying an experiment to evaluate the positive and negative aspects of metal-to-metal adhesion. During a future manned space flight, an attempt might be made to repair a defective printed circuit board in an equipment module. To perform this task, the circuit board must be removed from the module connector, repaired, and reinserted in the module. To ensure the success of this experiment, MSFC must be assured that adhesion will not prevent removal of the printed circuit board from the module, or its replacement after repair. At the same time it would be desirable to use the adhesion phenomenon in the design of tooling for repair purposes.

A state-of-the-art survey of the field of adhesion was conducted to provide MSFC with the information required for planning this experiment. The behavior of metals and metal surfaces in a vacuum characteristic of those to be encountered at altitudes of several hundred miles is emphasized in this report. Rather than confine this survey to the effects of ultrahigh vacuum on the metals used in electrical contacts and connectors alone, the entire field of metal-to-metal adhesion was surveyed. Extensive research on adhesion phenomena has been conducted since the early 1930's, and much of the present knowledge of adhesion is based on the results of investigations undertaken by those interested in friction, wear, and lubrication. With the advent of the space age, problems associated with adhesion were encountered -- problems which, in some instances, affected the performance of spacecraft equipment. Since the attainment of programmed objectives is largely dependent on our ability to predict materials behavior in the space environment, large-scale programs to investigate adhesion and friction under simulated space conditions have been undertaken. Most of the research has been concentrated on the prevention of adhesion,

and extensive studies on the fundamental nature of adhesion and the development of improved lubricants for space applications have been conducted. The emphasis on this aspect of adhesion is understandable because of the pressing need for such information; however, research to promote adhesion is also needed.

A review of the published literature indicates there is little correlation between the individual adhesion and friction data obtained by various organizations, but there is considerable agreement on the general behavior of specific metal combinations. The lack of correlation is not surprising, since the objective of the research program ranges from a fundamental study of adhesion to the development of a lubricant for a specific application. Also, there is a complete lack of standardization in the specimen design, the metal surface preparation, the test environment, and the test procedures.

The available information indicates substantial agreement on the following measures to minimize adhesion:

1) Use hard metals that have high elastic moduli and low ductility.
2) Use minimum contact pressures on metal surfaces.
3) Avoid operating temperatures exceeding one-half of the absolute melting temperature of the metals.
4) Avoid sliding motion between metal surfaces.

Research has also indicated that dissimilar metal couples bond less readily than similar metal couples, metals with a hexagonal crystal lattice structure have a lower coefficient of friction than metals with a cubic lattice structure, and metals with widely differing atomic diameters bond less readily than metals with similar atomic diameters. However, more research on these aspects of adhesion is needed to substantiate them as methods to minimize adhesion.

Generally, metal-to-metal adhesion can be enhanced by reversing the concepts listed above.

The phenomenon of adhesion or surface welding in the space environment is becoming increasingly important to those engaged in space exploration and research. While the major emphasis of current research is directed toward the prevention of undesirable adhesion of moving parts, the day when this phenomenon may be needed to fabricate or repair structures in space is rapidly approaching. Research to develop space welding techniques is already underway. Recently, the development of electron-beam equipment for welding in space was reported.[1] Current concepts of interplanetary travel envisage the use

of orbiting space stations from which flights to other planets can be launched. Such stations will provide facilities for the docking, fueling, and launching of space vehicles. In addition, these stations will supply the life-support requirements of the crew members and station personnel, as well as repair and rescue capabilities. Because of the planned size of these structures, it will be necessary to place individual sections of the stations in orbit and complete the structural assembly in space. Welding is a preferred method of assembly.

Section II. BACKGROUND

1. Adhesion Concepts

According to Semenov,[2] spontaneous adhesion of two pieces of the same metal would occur as the result of simple contact alone if the metal surfaces were smooth on a microscopic scale, the surfaces were perfectly clean, and the crystal lattices of the opposing surfaces had the same orientation. However, ideal adhesion does not occur because these requirements are not satisfied.

On the microscopic scale, a metal surface is not smooth. The most highly polished metal surface has numerous irregularities, whose peak-to-valley distances measure from 0.05 to 0.1μ; ground metal surfaces are much rougher, of course.[3] Even the smoothest surface, which is formed by the careful cleavage of mica, has irregularities on the order of 0.002μ. These irregularities prevent true metal-to-metal contact except where the projections or asperities of the opposing surfaces coincide. On the basis of resistance measurements, Anderson[4] estimates the real area of contact is about 10^{-6} times the area of apparent contact. In Figure 1, an artist's conception of the actual appearance of a very smooth copper surface is shown.

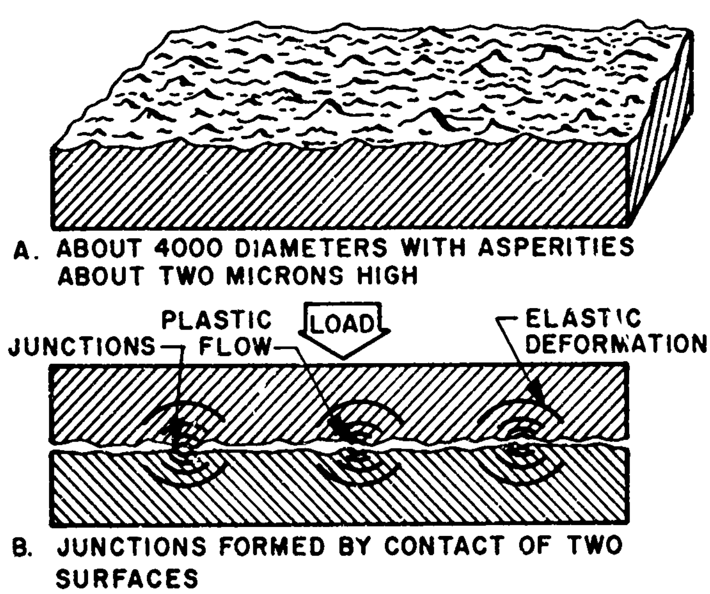


Figure 1. Enlarged Surface of "Smooth" Copper[4]

Metal surfaces are not clean. All metal surfaces exposed to air consist of at least three distinct layers:

1) A layer of adsorbed gases.
2) A layer of oxide.
3) The bulk metal itself.

The oxide structure may be single-layered or multi-layered. The layer of adsorbed gases is about 0.01μ thick, while the thickness of the oxide layer varies from about 0.001 to 10μ, depending on the composition of the metal and the environment. The oxide film on the noble metals may be only a few atomic layers thick; it is much thicker on most other metals.[5] These contaminating films form very quickly, even at very low pressures. Lewin[6] indicated that a monolayer of gas would form on a surface in about 4×10^{-9} second in air at atmospheric pressure; at a pressure of 10^{-6} torr, about three seconds would be required to form a similar film. At a pressure of about 10^{-7} torr, Hamm[7] estimated that a layer of FeO, one Å (0.0001μ) thick would form on iron at room temperature in one minute. It is generally agreed that the presence of surface contaminants is the major factor that prevents adhesion.

Precise orientation of the crystal lattices of the opposing surfaces of polycrystalline metals is impossible to attain. Thus, adhesion cannot be obtained without some distortion of the crystal lattices of surface layers; in other words, an energy barrier must be overcome. The energy required for crystal lattice reorientation can be supplied by pressure, heat, deformation, etc.

The control of adhesion in the terrestrial environment is relatively simple, since there are numerous means to promote or prevent bonding. Lubricants of many types are available to minimize friction, wear, and seizure. The normal surface condition of a metal (i.e., covered with films of oxides and adsorbed gases) is a deterrent to bonding, and coatings are available that will virtually ensure nonadhesion. On the other hand, the tendency toward bonding can be enhanced by careful preparation of the faying surfaces of the parts being joined. Coatings or platings can be used to produce weldable surfaces and to promote alloying. Perhaps the most effective means to ensure bonding is the ability to control the bonding variables such as temperature, pressure, time, deformation, etc.

Many of the means to control adhesion discussed above are not available in the space environment. For example, lubricants for space applications must be carefully selected, since many vaporize and lose

effectiveness in the hard vacuum of outer space. Similarly, oxides, films of adsorbed gases, and the coatings used to minimize adhesion can be removed from metal surfaces in space by evaporation, dissociation, or diffusion into the metal. Once removed, these surface contaminants cannot reform or reform very slowly. Abrasion, caused by the sliding motion of electrical and mechanical devices, can remove these contaminants also. However, joining in space may be enhanced by the environment. For example, mating surfaces can be coated or plated with a material that will prevent adhesion on earth and will evaporate to promote adhesion in space. Also, as will be discussed later, certain metal couples bond more easily than others. However, joining operations in space are somewhat limited by the lack of precise control of the bonding variables.

Adhesion is defined classically as the molecular attraction exerted between bodies in contact, while cohesion is defined as the molecular attraction by which particles of a body are united throughout the mass, whether like or unlike. Some ambiguity concerning these definitions has occurred in recent years. Some investigators use the term "cohesion" to refer to the bonding of similar metals, while the term "adhesion" is reserved for the bonding of dissimilar metals. Adhesion will be used in the accepted sense in this report, except when discussing the results of research by organizations that observe the above distinctions.

Adhesion is a solid-state joining process in which two or more phases are metallurgically joined without the creation of a liquid phase. The phenomenon of adhesion most closely resembles deformation welding in which plastic deformation is the major factor in the formation of the weld. Diffusion is not required to produce bonding. The term "cold welding" is also used as a synonym for adhesion. Two theories that attempt to explain the mechanism of deformation welding exist. According to the film theory, welding will occur when two clean metal surfaces are brought into contact; however, plastic deformation is needed to disrupt surface films that prevent intimate metal-to-metal contact. The energy barrier theory contends that welding will not occur even if clean metal surfaces are brought into intimate contact, because an energy barrier must be overcome before welding can occur. Plastic deformation provides this energy.

However, the undesired adhesion or bonding of space vehicle components which are exposed to the space environment constitutes an immediate, serious problem. Components with moving parts such as valves, bearings, hinges, and certain electrical parts must function after long-time exposure to the hard vacuum of outer space. Several

instances of equipment malfunctioning have been reported in the literature as discussed below.

During the operation of Surveyor I on the lunar surface, a potentiometer that was used to indicate the position of the azimuth axis showed signs of failing after operating for about 100 hours.[8] Because of outgassing problems with lubricants in the lunar environment and because of its proximity to the camera mirror, the potentiometer was not lubricated. Failure presumably occurred due to seizure of the wiper contact to the potentiometer winding after numerous operations. Improved potentiometers with a dry, nonoutgassing, lubricant are expected to be used on later Surveyor spacecraft. During the flight of an Air Force research satellite, the signal strength from the satellite was lower than expected and the spin rate was higher; however, over a period of several weeks, the signal strength increased, the spin rate decreased, and satisfactory performance was eventually obtained.[9] These malfunctions were traced to the apparent failure of a gold-plated antenna to unfold when orbit was attained. During launch, the rolled-up antenna was stowed in a retaining cup. As the result of extended vibration during launch, the antenna rubbed against the retaining cup, and some of the plating was worn away. Cold welding occurred at various locations along the antenna when the satellite entered space, and the programmed folding did not occur. In orbit, the antenna experienced thermal shock as the satellite passed from hot to cold areas, and the welds opened gradually to permit unfolding of the antenna. The improvement in signal strength correlated with such a process, and the data were verified later by laboratory tests. During the Gemini 4 flight, the astronauts' hatch door jammed momentarily during the extra-vehicular activity.[9] The jamming could have been caused by seizure of the hatch hinges. One hinge member is made from titanium, while hard-coated aluminum is used for the other member. A dry film lubricant is applied to the rubbing surfaces to prevent seizure. There was evidence that the lubricant had been inadvertently removed before launch.[10]

In 1961, the Air Force attempted to orbit 50 pounds of fine copper wires or needles at an altitude of 2000 miles in experiment West Ford. The experiment was not successful, possibly because the needles cold-welded to one another.[11] It was reported that benzene was used as the adhesive to hold the 10^{-6} mm diameter needles together during the preliminary phases of the experiment. It was expected that the benzene would vaporize in space, leaving the separate needles ready for ejection. This premise was validated by laboratory tests conducted in a vacuum of 10^{-6} torr. However, after the failure of experiment West Ford, the tests were repeated in a vacuum of 10^{-10} torr. Under these conditions, the needles adhered to one another. Since the pressure at an altitude of 2000 miles (about 8×10^{-13} torr) is lower than the test vacuum, adhesion was apparently the cause of failure.

Extensive research on adhesion and various related subjects has been conducted. While much of the recent and current research has been sponsored by Government agencies interested in space applications, important contributions to the basic understanding of adhesion have been made by industry and university research organizations. Because of the broadness of the topic of adhesion, the areas of technology covered by this report are discussed below.

As its major objective, this report summarizes the information on the adhesion of electrical connections in the space environment. While there may be occasions when it is desirable to use the phenomenon of adhesion to produce electrical connections in space, the equipment designer is much more concerned with the prevention of adhesion. Many electrical components and devices such as switches, relays, slip-rings, connectors, and potentiometers depend on sliding motion to ensure electrical continuity of the contacting surfaces. Such connections must function reliably after varying periods of exposure to the space environment. The reliable operation of these components in the terrestrial environment is taken for granted. Depending on the quality of the device, contact can be made and broken indefinitely without failure. However, similar performance under space conditions cannot be assumed, since sliding motion tends to denude the contacting surfaces of films and oxides that are normally present under atmospheric conditions. Because these media cannot reform in the ultrahigh vacuum of outer space, nascent metal is exposed and contacting surfaces can adhere to one another. Even before the circuit becomes completely inoperative, the performance of the electrical device can degenerate to produce undesired signals or noise in the circuit. Although hermetic sealing of electrical components and circuitry could be used to eliminate the effects of the vacuum environment, such procedures increase the size, weight, and complexity of the equipment while bypassing the problem of adhesion. Similar disadvantages are associated with the use of redundant circuit elements to ensure reliability.

Since the emphasis of this report is on the adhesion of electrical connections, the report is likewise primarily concerned with the metals used in the construction and plating of contacts. Included among these metals are gold, silver, copper, zinc, cadmium, chromium, molybdenum, and thallium. However, the research reported in this publication is not restricted to these metals alone, because of the following:

1) Adhesion data on certain of the metals above is limited or non-existant.
2) Important contributions to the technology of adhesion have been made during studies with the more common structural metals.

3) Since the tendency for adhesion to occur is related to the physical properties of the elements themselves, a broad spectrum of metals should be included in this survey.

2. Operating Environments for Spacecraft

In designing equipment for service in space, man is faced with the necessity to consider operations in not one but several different environments. These environments are associated with the following activities:

1) On the ground.
2) During launch, ascent, and reentry.
3) During long-time operation in space.[12]

The conditions imposed by these environments have an important bearing on adhesion and related subjects such as friction, wear, and lubrication.

During the normal ground activities prior to launch, the mechanisms used in spacecraft are operated repeatedly to test components and entire systems. Thus, parts that may operate momentarily during the launch cycle actually accumulate many hours of operation. The lubricants used in these mechanisms must therefore be equally effective in both the terrestrial and space environments. Similarly, electrical contacts receive many hours of operation before launch and must be designed to withstand such service. In addition to problems caused by test and checkout operations, the designer must consider the potential hazards created by the launch-site environment. Delicate mechanisms must be protected from rain, mist, fog, sand, and dust as well as salt spray and high-humidity conditions. Electrical parts are particularly sensitive to such conditions.

During the launch, ascent, and reentry cycles, the mechanisms used in spacecraft are subjected to a wide variety of environmental conditions ranging from those encountered on the ground to those encountered in outer space; in addition, extremes of vibration, shock, and acceleration are experienced. As the spacecraft ascends through the lower atmosphere, the air behaves as a continuous medium or compressive fluid. Aerodynamic heating is encountered as the kinetic energy of motion is converted to thermal energy by compression of the medium and by friction between the fluid particles. At altitudes above 300 kilometers, the mean-free path of the gas molecules exceeds the dimensions of the spacecraft, and aerodynamic heating is no longer

significant. During the ascent cycle, the pressure drops rapidly from 760 torr at sea level to about 10^{-6} torr at an altitude of 125 miles to 10^{-9} torr at 500 miles and lower at higher altitudes. Heavy shock and vibration loads occur during the launch and ascent period also. Thus, for this environment, lubricants must be effective at both high and low temperatures and pressures. Bearings must be designed to withstand the expected vibration and shock loads. Electrical devices whose performance depends on sliding motions are particularly sensitive to vibration, since repeated small motions can damage contacting surfaces.

Satellites and other spacecraft that operate in orbit are subjected to such conditions as ultrahigh vacuum, temperature extremes, zero gravity, and various types of radiation. The space environment and its effect on electrical and mechanical devices is discussed in the following section. The aspects of operations in the hard vacuum of outer space will be emphasized.

3. Space Environment Characteristics

The space environment is extremely complex. During the past eight years, extensive knowledge on its structure and effect on spacecraft materials has been acquired through space exploration. The general outline of the space environment is well established; however, there are gaps in the knowledge, particularly in the description of the radiation environment, that remain to be filled. Many problems with the effects of the space environment on surfaces have been encountered, and much remains to be done in detailing the effects of certain aspects of this environment on emittance, reflectivity, absorptance, sliding friction, etc. These effects are difficult to study in the terrestrial environment, because of the problems associated with the simulation of space conditions. It is difficult enough to simulate such individual aspects of the space environment as ultrahigh vacuum, solar radiation, and thermal radiation. It is much harder to simulate a combined environment.

The major regions of the earth's atmosphere and their characteristic features are given in Table I.[13] The properties of the atmosphere below an altitude of 56 miles are best described in the U. S. Standard Atmosphere.[14] In calculating accurate data for the atmosphere above 56 miles, it is necessary to account for variations caused by time (hour, day, year, season, and sunspot cycle), location (altitude, latitude, and longitude), solar activity (ultraviolet radiation, solar plasms, and magnetic storms), and processes (diffusion, ionization, dissociation,

Table I. Main Regions of the Earth's Atmosphere[13]

Atmospheric Region	Subregion	Approximate Altitude Range (sm)	Characteristic Features
Homosphere	Troposphere	0 to 7	Mean molecular weight constant; heat transfer by convection
	Stratosphere	7 to 30	Constant molecular weight; increasing temperatures; region strongly heated by both earth infrared and solar ultraviolet radiation
	Mesosphere	30 to 56	Constant molecular weight; decreasing temperature. Mixing processes dominant throughout homosphere
Heterosphere	Thermosphere	56 to 340	Frequent particle collisions; diffusion process dominant
	Exosphere	340 to 37,000	Collisions rare, temperature constant to about 5300sm; diffusion process dominant

recombination, etc.). Since upper atmosphere measurements are not made on a regular enough basis, a mathematical model is usually used in determining the desired properties. Tables II and III show the properties of the upper atmosphere from altitudes of 100 to 10,000 kilometers as calculated with such a model.[13, 15] Data at sunspot maximum and minimum are given to show the variation in properties caused by sunspot activity. The variation in the density of the atmosphere as a function of altitude is shown in Figure 2.

Since a discussion of the effects of the space environment on the properties of all materials used in spacecraft is beyond the scope of this report, the following sections will be devoted to a consideration of the effect of certain space conditions on metals, metal surfaces, and the materials used to prevent adhesion. Most metals are quite stable in the space environment from the engineering strength standpoint, but surface properties change significantly with long-time exposure.

Table II. Neutral Properties of Upper Atmosphere at Sunspot Maximum for Various Altitudes[13]

Altitude		Pressure*	Temper-ature	Molecular Weight	Scale Height	Density*	Concentration*						
							Total	Constituent (cm^{-3})					
(km)	(sm)	(torr)	(°K)		(km)	(gm/cm^3)	(cm^{-3})	$n(N_2)$	$N(O_2)$	n(N)	n(O)	n(He)	n(H)
100	62.1	4.4 (-4)	208	28.04	6.49	9.59 (-10)	2.06 (13)	1.60 (13)	3.50 (12)	1.50 (9)	1.10 (12)	7.00 (7)	1.50 (5)
120	74.6	3.6 (-5)	324	26.62	10.7	4.75 (-11)	1.07 (12)	7.91 (11)	1.20 (11)	2.67 (8)	1.63 (11)	3.12 (7)	8.78 (4)
140	87.0	8.9 (-6)	636	25.21	22.4	5.69 (-12)	1.36 (11)	8.97 (10)	1.10 (10)	6.43 (7)	3.52 (10)	1.28 (7)	4.24 (4)
160	99.4	4.3 (-6)	850	24.21	31.3	1.94 (-12)	4.83 (10)	2.89 (10)	3.13 (9)	3.15 (7)	1.63 (10)	8.49 (6)	3.08 (4)
180	111.9	2.4 (-6)	970	23.31	37.3	9.13 (-13)	2.36 (10)	1.27 (10)	1.25 (9)	1.95 (7)	9.62 (9)	6.74 (6)	2.63 (4)
200	124.3	1.4 (-6)	1060	22.47	42.6	4.89 (-13)	1.31 (10)	6.31 (9)	5.69 (8)	1.32 (7)	6.21 (9)	5.66 (6)	2.36 (4)
250	155.3	4.9 (-7)	1133	20.59	50.4	1.43 (-13)	4.19 (9)	1.46 (9)	1.08 (8)	6.15 (6)	2.62 (9)	4.34 (6)	2.10 (4)
300	186.4	1.9 (-7)	1157	19.05	56.5	5.10 (-14)	1.61 (9)	3.82 (8)	2.34 (7)	3.11 (6)	1.20 (9)	3.52 (6)	1.96 (4)
350	217	8.3 (-8)	1167	17.91	61.5	2.04 (-14)	6.86 (8)	1.05 (8)	5.32 (6)	1.62 (6)	5.73 (8)	2.90 (6)	1.86 (4)
400	249	3.8 (-8)	1175	17.11	65.8	8.83 (-15)	3.11 (8)	2.96 (7)	1.26 (6)	8.58 (5)	2.77 (8)	2.41 (6)	1.76 (4)
500	311	8.9 (-9)	1175	16.15	71.8	1.95 (-15)	7.27 (7)	2.55 (6)	7.64 (4)	2.52 (5)	6.84 (7)	1.70 (6)	1.61 (4)
600	373	2.3 (-9)	1175	15.38	77.6	4.85 (-16)	1.90 (7)	2.36 (5)	5.03 (3)	7.65 (4)	1.75 (7)	1.21 (6)	1.48 (4)
700	435	6.8 (-10)	1175	14.15	86.8	1.31 (-16)	5.58 (6)	2.33 (4)	3.57 (2)	2.41 (4)	4.68 (6)	8.67 (5)	1.37 (4)
800	497	2.4 (-10)	1175	12.02	105	3.87 (-17)	1.94 (6)	2.46 (3)	2.73 (1)	7.84 (3)	1.29 (6)	6.29 (5)	1.26 (4)
900	559	1.0 (-10)	1175	9.24	140	1.29 (-17)	8.42 (5)	2.76 (2)	2.24 (0)	2.63 (3)	3.71 (5)	4.68 (5)	1.17 (4)
1000	621	5.6 (-11)	1175	6.80	196	5.19 (-18)	4.60 (5)	3.29 (1)		9.05 (2)	1.10 (5)	3.40 (5)	1.08 (4)
1200	746	2.5 (-11)	1175	4.48	314	1.56 (-18)	2.09 (5)			1.17 (2)	1.06 (4)	1.89 (5)	9.34 (3)
1400	870	1.4 (-11)	1175	3.91	379	7.67 (-19)	1.18 (5)			1.68 (1)	1.16 (3)	1.09 (5)	8.13 (3)
1600	994	8.7 (-12)	1175	3.73	419	4.43 (-19)	7.16 (4)			2.67 (0)	1.41 (2)	6.43 (4)	7.13 (3)
1800	1119	5.5 (-12)	1175	3.59	457	2.70 (-19)	1.53 (4)				1.91 (1)	3.90 (4)	6.29 (3)
2000	1243	3.6 (-12)	1175	3.44	500	1.70 (-19)	2.98 (4)				2.84 (0)	2.42 (4)	5.58 (3)
2500	1553	1.5 (-12)	1175	2.97	651	6.07 (-20)	1.23 (4)					8.08 (3)	4.24 (3)
3000	1864	7.7 (-13)	1175	2.48	886	2.56 (-20)	6.35 (3)					3.03 (3)	3.32 (3)
3500	2175	4.8 (-13)	1175	1.96	1219	1.28 (-20)	3.92 (3)					1.26 (3)	2.66 (3)
4000	2486	3.3 (-13)	1175	1.62	1631	7.38 (-21)	2.75 (3)					5.67 (2)	2.18 (3)
4500	2796	2.5 (-13)	1175	1.39	2081	1.85 (-21)	2.10 (3)					2.75 (2)	1.82 (3)
5000	3107	2.1 (-13)	1175	1.25	2532	[illegible].51 (-21)	1.69 (3)					1.42 (2)	1.55 (3)
6000	3728	1.5 (-13)	1175	1.11	3378	2.22 (-21)	1.20 (3)					4.46 (1)	1.16 (3)
7000	[illegible]350	1.1 (-13)	1175	1.05	4160	1.61 (-21)	9.21 (2)					1.66 (1)	9.04 (2)
8000	4971	9.0 (-14)	1175	1.03	4923	1.26 (-21)	7.38 (2)					7.13 (0)	7.31 (2)
9000	5592	7.4 (-14)	1175	1.02	5700	1.03 (-21)	6.11 (2)					3.40 (0)	6.08 (2)
10,000	6214	6.3 (-14)	1175	1.01	6506	8.70 (-22)	5.19 (2)					1.78 (0)	5.17 (2)

*Number inside parenthesis denotes power of 10, thus 1.4 (-4) means 1.4×10^{-4}.

Table III. Neutral Properties of Upper Atmosphere at Sunspot Minimum for Various Altitudes[13]

Altitude		Pressure*	Temper-ature	Molecular Weight	Scale Height	Density*	Concentration*						
							Total	Constituent (cm^{-3})					
(km)	(sm)	(torr)	(°K)		(km)	(gm/cm^3)	(cm^{-3})	$n(N_2)$	$n(O_2)$	$n(N)$	$n(O)$	$n(He)$	$n(H)$
100	62.1	1.0 (-4)	205	28.25	6.35	2.25 (-10)	4.80 (12)	3.70 (12)	9.00 (11)	1.00 (9)	2.00 (11)	2.20 (7)	5.00 (5)
120	74.6	7.5 (-6)	310	26.98	10.1	1.04 (-11)	2.33 (11)	1.74 (11)	2.91 (10)	1.77 (8)	2.93 (10)	9.98 (6)	3.01 (5)
140	87.0	1.9 (-6)	560	25.74	19.3	1.36 (-12)	3.19 (10)	2.20 (10)	2.96 (9)	4.66 (7)	6.94 (9)	4.47 (6)	1.58 (5)
160	89.4	7.7 (-7)	745	24.67	26.9	4.11 (-13)	1.00 (10)	6.28 (9)	7.36 (8)	2.16 (7)	3.00 (9)	2.93 (6)	1.15 (5)
180	111.9	4.0 (-7)	860	23.68	32.6	1.75 (-13)	4.45 (9)	2.50 (9)	2.63 (8)	1.27 (7)	1.61 (9)	2.27 (6)	9.67 (4)
200	124.3	2.2 (-7)	925	22.73	36.7	8.77 (-14)	2.32 (9)	1.16 (9)	1.10 (8)	8.33 (6)	1.04 (9)	1.91 (6)	8.77 (4)
250	155.3	6.5 (-8)	990	20.55	44.1	2.17 (-14)	6.35 (8)	2.20 (8)	1.67 (7)	3.51 (6)	3.93 (8)	1.42 (6)	7.74 (4)
300	186.4	2.2 (-8)	1000	18.78	49.5	6.74 (-15)	2.16 (8)	4.77 (7)	2.91 (6)	1.63 (6)	1.63 (8)	1.13 (6)	7.26 (4)
350	217	8.5 (-9)	1000	17.50	53.9	2.39 (-15)	8.24 (7)	1.07 (7)	5.28 (5)	7.70 (5)	6.94 (7)	9.15 (5)	6.88 (4)
400	249	3.5 (-9)	1000	16.61	57.7	9.28 (-16)	3.36 (7)	2.46 (6)	9.83 (4)	3.69 (5)	2.98 (7)	7.41 (5)	6.52 (4)
500	311	6.8 (-10)	1000	15.20	64.9	1.65 (-16)	6.55 (6)	1.38 (5)	3.66 (3)	8.74 (4)	5.77 (6)	4.91 (5)	5.89 (4)
600	373	1.6 (-10)	1000	13.03	77.9	3.42 (-17)	1.58 (6)	8.41 (3)	1.49 (2)	2.16 (4)	1.17 (6)	3.29 (5)	5.33 (4)
700	435	5.4 (-11)	1000	9.50	110	8.28 (-18)	5.25 (5)	5.55 (2)	6.69 (0)	5.54 (2)	2.47 (5)	2.23 (5)	4.84 (4)
800	497	2.6 (-11)	1000	6.13	175	2.58 (-18)	2.53 (5)	3.95 (1)		1.48 (3)	5.45 (4)	1.53 (5)	4.40 (4)
900	559	1.6 (-11)	1000	4.22	262	1.11 (-18)	1.59 (5)	3.02 (0)		4.09 (2)	1.26 (4)	1.06 (5)	4.01 (4)
1000	621	1.2 (-11)	1000	3.36	338	6.36 (-19)	1.14 (5)			1.17 (2)	3.01 (3)	7.42 (4)	3.67 (4)
1200	746	7.1 (-12)	1000	2.68	447	3.05 (-19)	6.85 (4)			1.06 (1)	1.93 (2)	3.74 (4)	3.09 (4)
1400	870	4.7 (-12)	1000	2.28	553	1.73 (-19)	4.58 (4)			1.09 (0)	1.43 (1)	1.95 (4)	2.63 (4)
1600	994	3.4 (-12)	1000	1.95	679	1.07 (-19)	3.30 (4)				1.21 (0)	1.05 (4)	2.25 (4)
1800	1119	2.6 (-12)	1000	1.69	824	7.10 (-20)	2.53 (4)					5.84 (3)	1.94 (4)
2000	1243	2.1 (-12)	1000	1.49	980	5.02 (-20)	2.02 (4)					3.33 (3)	1.69 (4)
2500	1553	1.4 (-12)	1000	1.21	1359	2.64 (-20)	1.32 (4)					9.18 (2)	1.22 (4)
3000	1864	9.8 (-13)	1000	1.09	1680	1.72 (-20)	9.47 (3)					2.90 (2)	9.18 (3)
3500	2175	7.4 (-13)	1000	1.04	1951	1.24 (-20)	7.19 (3)					1.03 (2)	7.09 (3)
4000	2486	5.9 (-13)	1000	1.02	2199	9.58 (-21)	5.65 (3)					4.04 (1)	5.61 (3)
4500	2796	4.7 (-13)	1000	1.01	2440	7.65 (-21)	4.55 (3)					1.73 (1)	4.54 (3)
5000	3107	3.9 (-13)	1000	1.01	2683	6.26 (-21)	3.74 (3)					7.97 (0)	3.74 (3)
6000	3728	2.8 (-13)	1000	1.00	3198	4.43 (-21)	2.66 (3)					2.04 (0)	2.66 (3)
7000	4350	2.1 (-13)	1000	1.00	3729	3.31 (-21)	1.99 (3)						1.99 (3)
8000	4971	1.6 (-13)	1000	1.00	4309	2.58 (-21)	1.55 (3)						1.55 (3)
9000	5592	1.3 (-13)	1000	1.00	4931	2.07 (-21)	1.25 (3)						1.25 (3)
10,000	6214	1.1 (-13)	1000	1.00	5593	1.71 (-21)	1.03 (3)						1.03 (3)

*Number inside parenthesis denotes power of 10, thus 4.4 (-4) means 4.4×10^{-4}.

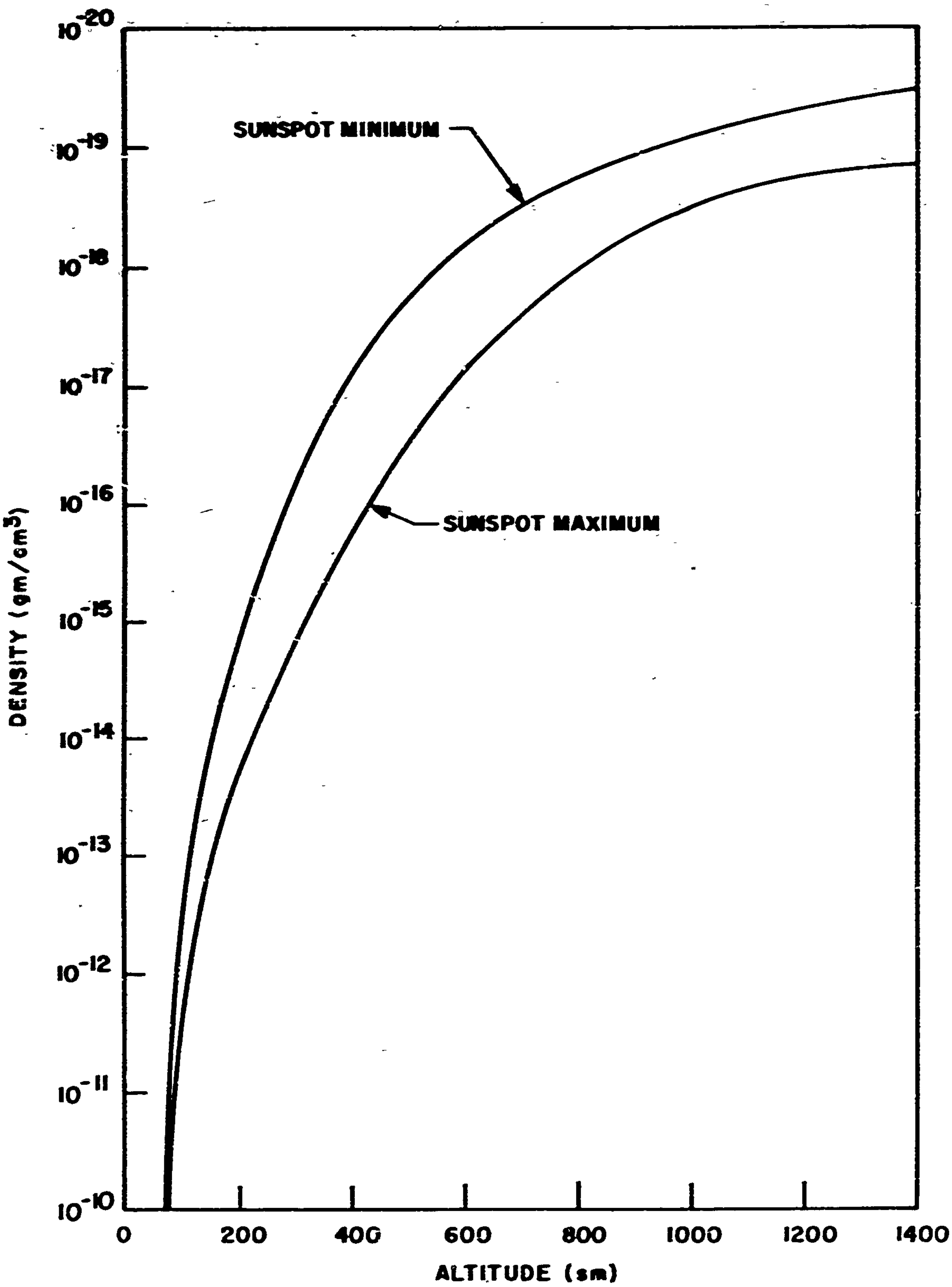


Figure 2. Average Atmospheric Density at Extremes of Sunspot Cycle

a. Effect of Ultrahigh Vacuum

Whenever extremely low environmental pressures are encountered, the direct evaporation of metals must be considered. When the environmental pressure is so low that the mean-free path of the vaporized molecules is long in comparison with the dimensions of the evaporating structure, recondensation is no longer significant and the rate of evaporation is dependent only on the surface temperature and the corresponding vapor pressure of the metal. Such is the case at altitudes of about 120 kilometers where the mean-free path exceeds one meter.

The Langmuir equation, as shown below, can be used to calculate the rate of evaporation or sublimation of metals. The results of such calculations for elemental metals and semiconductors are tabulated in terms of the temperature at which various thicknesses of metal will evaporate in one year in Table IV.[16] At the temperatures likely to be encountered by spacecraft (about -73° to 83°C for the Agena satellites) in orbit, cadmium, selenium, and zinc will suffer appreciable losses through evaporation, but none of these metals is used for structural purposes. However, the use of cadmium plating on electrical contacts exposed to the space environment should be avoided. Magnesium will lose less than 0.001 centimeter per year by evaporation unless the temperature exceeds 170°C. While such a loss is unimportant when magnesium is used for structural purposes, it could be significant if a magnesium film were used for its optical properties. The evaporation rates for other metals likely to be used in the spacecraft are insignificant at the expected surface temperatures. Data on the vapor pressures of the solid and liquid elements have been compiled by Honig (Figure 3).[17]

$$W = \frac{P}{17.14} \left(\frac{M}{T}\right)^{1/2}$$

where W = rate of evaporation, gm/cm^2-sec,
P = vapor pressure of the metal, torr,
M = molecular weight of the material,
T = temperature, °K.

The effect of ultrahigh vacuum on the oxides and films of adsorbed gases on metal surfaces is important from the adhesion standpoint, since these contaminants cannot reform under these conditions. Oxide films can be removed by evaporation, dissociation, diffusion, and by a combination of diffusion and chemical reaction. The results of a series of calculations by Hamm[7] on the rates of oxide removal are given in Table V (data are also included on metal evaporation rates) and Figures 4 and 5.

Table IV. Sublimation of Metals and Semiconductors in High Vacuum[16]*

Element**	Temperature (°C) at Which Sublimation Rate is		
	1000 Å/yr	10^{-3}cm/yr	10^{-1}cm/yr
Cd	40	80	120
Se	50	80	120
Zn	70	130	180
Mg	110	170	240
Te	130	180	220
Li	150	210	280
Sb	210	270	300
Bi	240	320	400
Pb	270	330	430
In	400	500	610
Mn	450	540	650
Ag	480	590	700
Sn	550	660	800
Al	550	680	810
Be	620	700	840
Cu	630	760	900
Au	660	800	950
Ge	660	800	950
Cr	750	870	1000
Fe	770	900	1050
Si	790	920	1080
Ni	800	940	1090
Pd	810	940	1100
Co	820	960	1100
Ti	920	1070	1250
V	1020	1180	1350
Rh	1140	1330	1540
Pt	1160	1340	1560
B	1230	1420	1640
Zr	1280	1500	1740
Ir	1300	1500	1740
Mo	1380	1630	1900
C	1530	1680	1880
Ta	1780	2050	2300
Re	1820	2050	2300
W	1880	2150	2500

* XII International Astronautical Congress, Edited by R. M. L Baker and M. W. Makemson, 1963, Table I, p 335.

** Gaseous molecules taken as monatomic, except Se, Te, Sb, Bi taken as diatomic; C mean molecular weight taken as 24.

Table V. Metal Evaporation and Removal of Oxide Films from Metals[7, 19]

Approximately the Minimum Temperatures (°C) for Removal of 100 Å of Either Metal or Oxide in a Year

Material	Metal Evaporation*	Oxide Evaporation	Oxide Diffusion	Oxide Dissociation	Carbon Reduction
Mg	100	n	n	n	n
Al	p	n	n	n	n
Zn	60	n	n	n	n
Cd	20	n	n	n	n
Pb	p	n	n	n	n
Cu	580	n	n	510	n
Ag	n	n	n	-127	n
Cr	580	p	n	n	p
Fe	730	n	n	1040	< 100
Co	815	n	n	850	p
Ni	770	840	n	800	p
Ti	n	n	300	n	n
Zr	n	n	310	n	n
Mo	n	n	n	1050	180
W	n	n	n	1100	p

*From oxide-free surface or through porous oxide.
n--negligible compared to alternate mechanism of oxide removal.
p--probably an important factor.

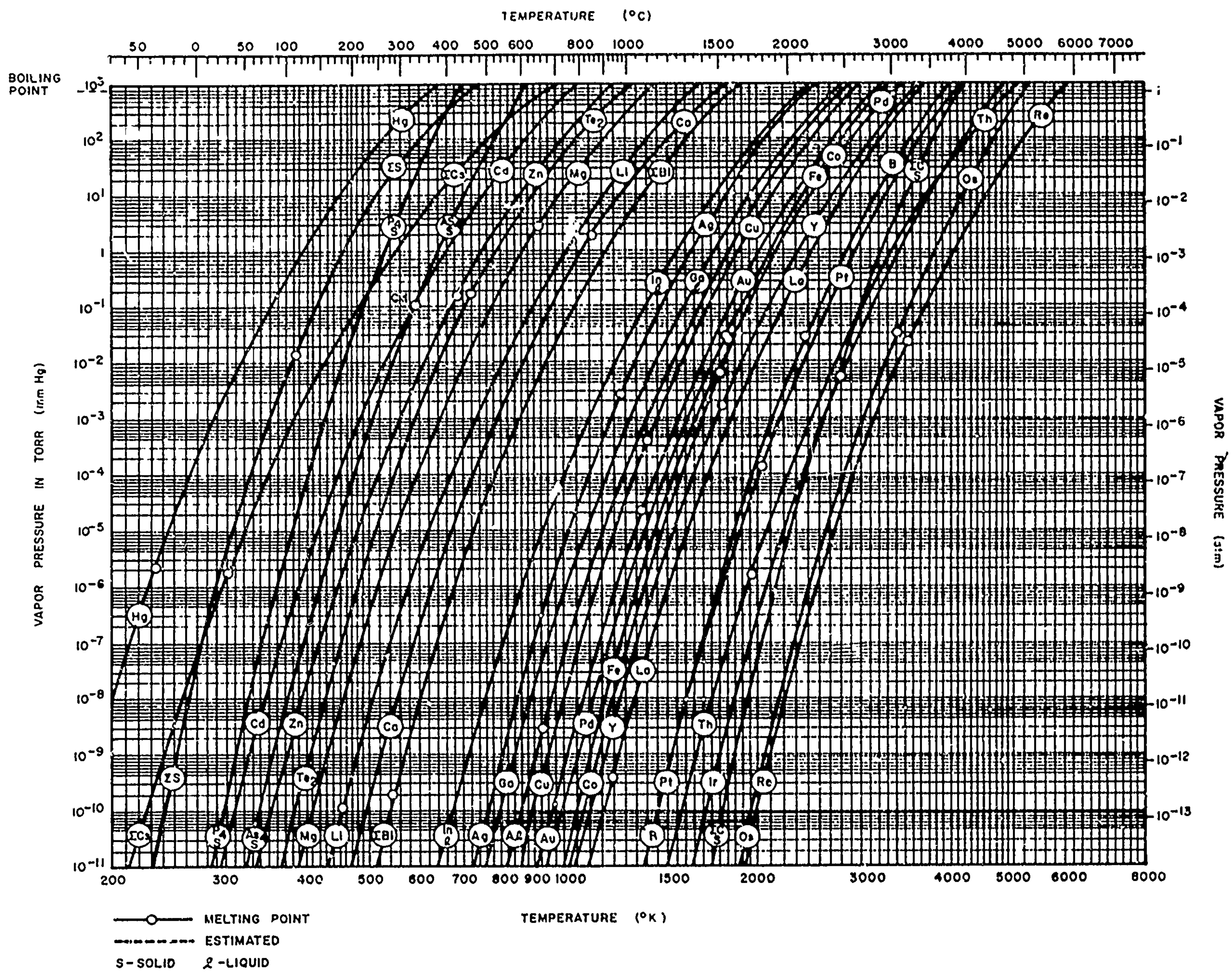


Figure 3. Vapor Pressure Data for the Solid and Liquid Elements[17]

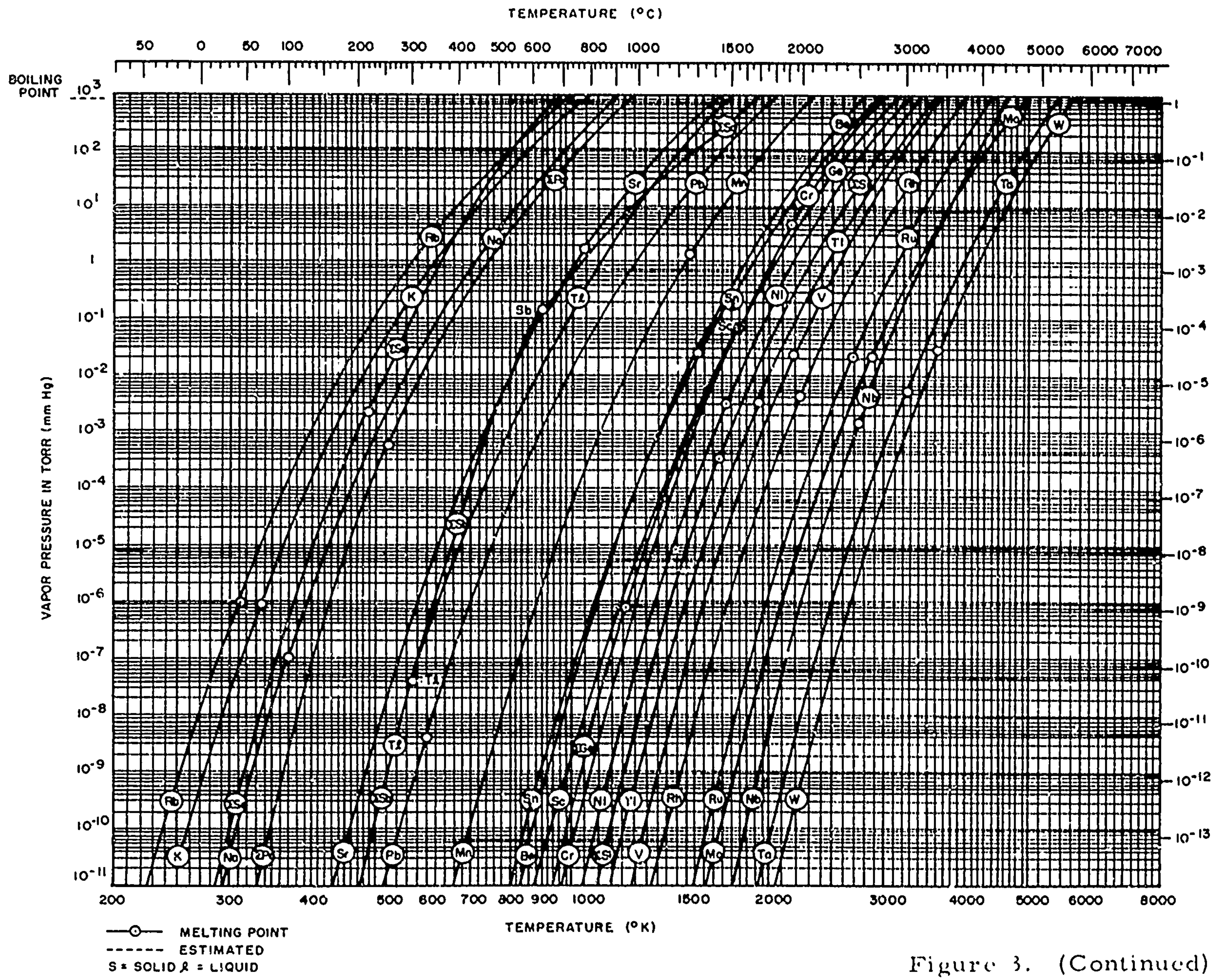


Figure 3. (Continued)

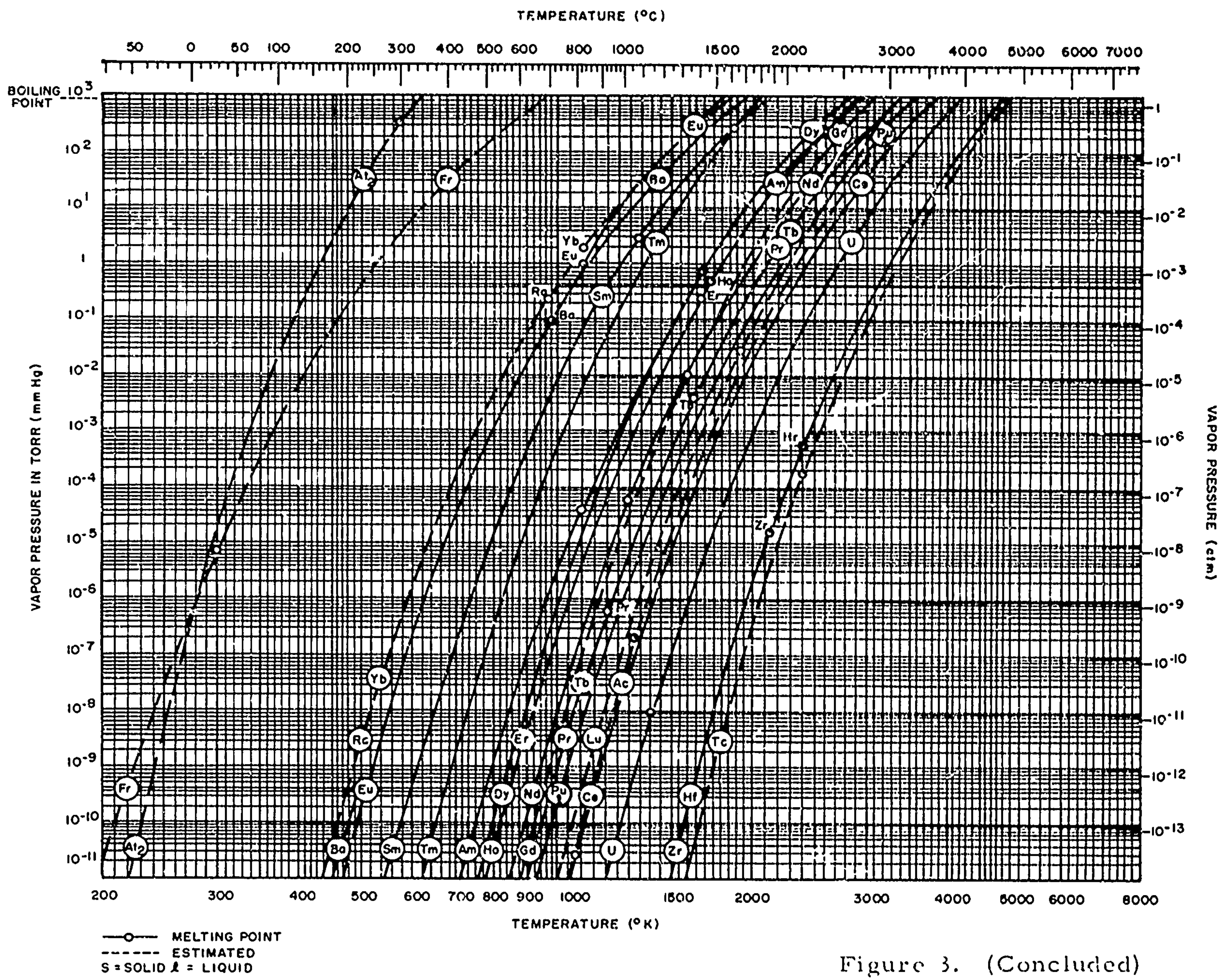


Figure 3. (Concluded)

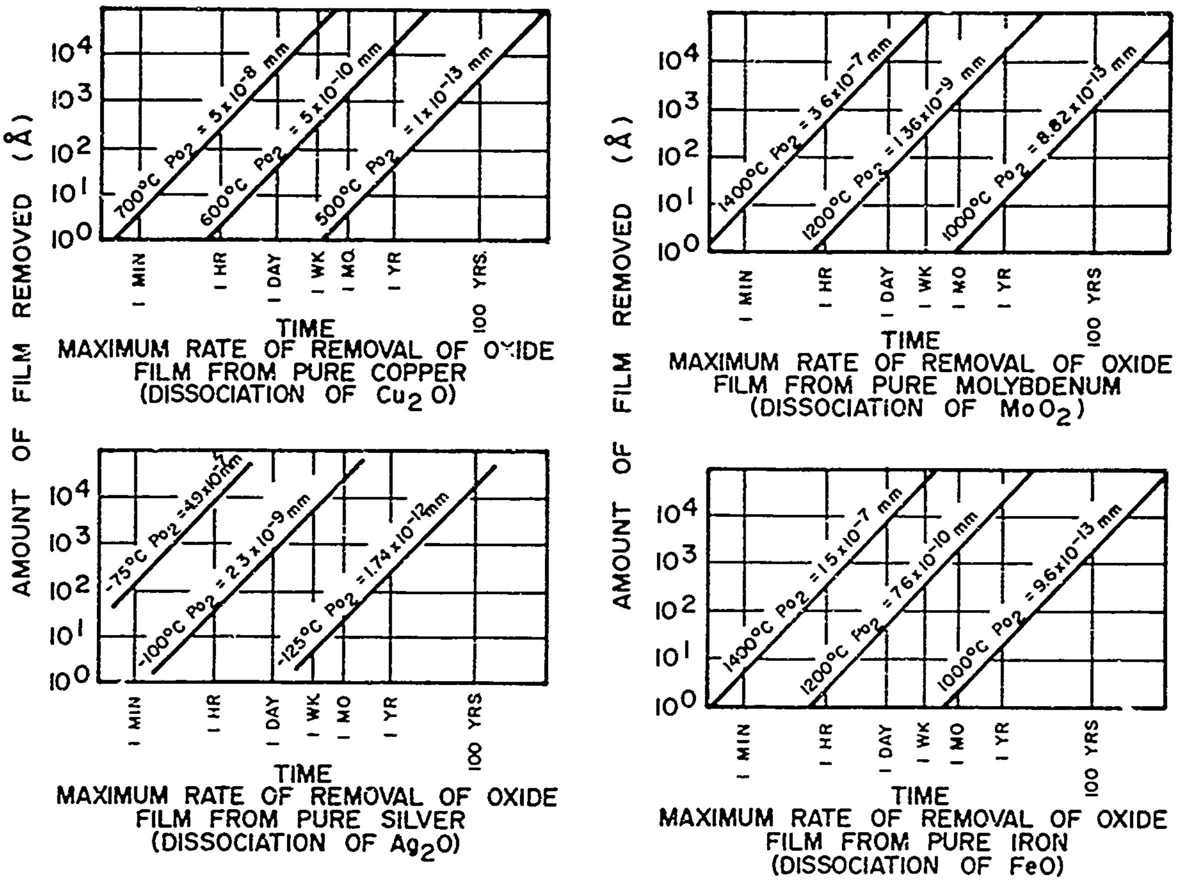


Figure 4. Dissociation of Oxides in a Vacuum[7, 19]

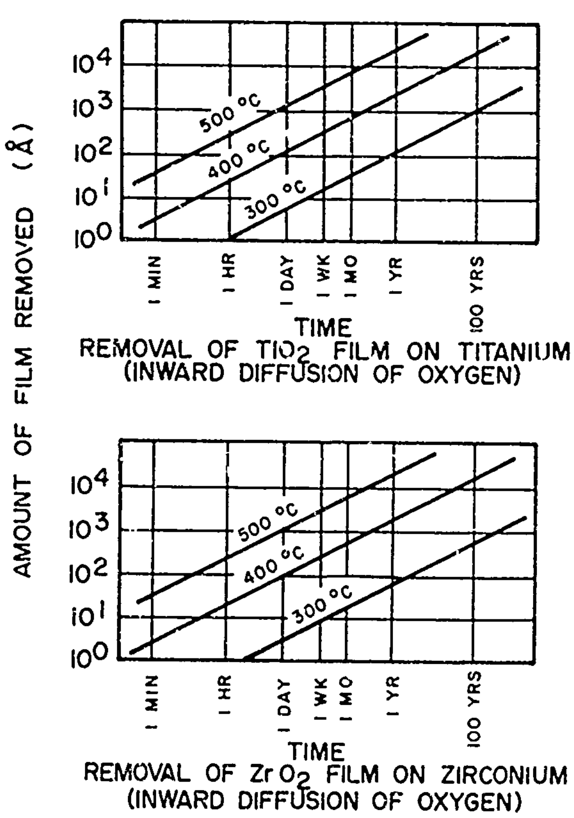


Figure 5. Removal of Oxides by Inward Diffusion of Oxygen[7, 19]

Except for the dissociation of silver oxide, the temperatures at which these phenomena occur are higher than the expected metal surface temperatures. The removal of silver oxide at a rate of 100 Å per year at -127°C in a vacuum of 10^{-12} torr may be significant, depending on the duration of the exposure period. Additional data on methods to calculate evaporation and dissociation rates have been provided by Dushman.[18] In some cases, the removal of adsorbed films of gases from metal surfaces may affect the mechanical properties of the metals. However, unless the composition or structure of the metal is altered by diffusion inward of the gaseous elements, or outward of volatile constituents, the metal is usually stronger in the vacuum than in a gas. Except for fatigue properties, no large strengthening effects have been noted.[19]

The effect of ultrahigh vacuum on the lubricants used to reduce frictional drag and minimize the power required to drive mechanisms is highly significant, since most conventional lubricants vaporize or otherwise lose their effectiveness in the space environment. Lubricants are subjected to environmental extremes, since they must function on the ground, during launch, ascent, and reentry, and in space. Extensive research has been conducted on the following classes of materials for space lubrication: oils and greases, laminar solids, plastics, soft metals, and ceramics. Laminar solids and soft metals appear to be most promising for operations in space. For detailed information in this research, the voluminous literature on lubricants, principles of lubrication, and related subjects should be consulted. Clauss and Young[13] provide an excellent state-of-the-art review in a recently published book. Annotated bibliographies on lubrication for space applications have been compiled by Abbott.[20, 21, 22]

b. Effect of Temperature

The operating temperature of a space vehicle is affected by its altitude, time of day, season, and latitude. The variation of temperature with altitude is given in Tables I and II; however, these temperatures are a measure of the kinetic energy of the atoms and molecules in the atmosphere at the indicated altitude, and they do not represent spacecraft temperatures. Aerodynamic heating is important at altitudes where the atmosphere has appreciable density. At altitudes above 300 kilometers, this type of heating is insignificant. Thus, the actual temperature of the spacecraft is dependent on solar radiation, earth reflection (albedo), earth emission, and emission of radiation from the vehicle itself. The spacecraft temperature is controlled by the ability of the space vehicle skin to absorb, reflect, emit, or transmit this

thermal energy. Elaborate means to accomplish these objectives have been developed with considerable success. The expected variation in surface temperature for the Agena satellite program was -100° to 200°F.

Such temperature variations are not expected to affect the mechanical properties of structural metals, although they may influence the rate at which oxides and films of adsorbed gases are removed from metal surfaces. The expected surface temperatures may be important when metals having widely different coefficients of expansion are joined; however, such problems can be overcome by proper material selection and joint design.

c. Effect of Sputtering

Sputtering, or the removal of atoms from the spacecraft surface by atomic or molecular bombardment, will be important at altitudes where high-velocity, solar-wind particles are encountered. The probability of sputtering is high when the energy level of the impinging particles exceeds a minimum threshold level of about 50 ev.[23] Assuming a low-intensity solar wind, Reiffel indicated that a 300 Å (0.03μ)-thick coating of aluminum would be destroyed in a month. During a solar storm, the same coating could be destroyed in a matter of hours. While such a loss of metal is unimportant from a strength standpoint, sputtering could seriously affect the optical and emissive properties of the space vehicle skin.

The mechanism of supttering has been used in adhesion studies as a means to clean metal surfaces in a vacuum.

d. Effect of Radiation

The effects of solar radiation, earth reflection, and earth emission on the surface temperature of a near-earth satellite has been already discussed. Penetrating radiation such as cosmic rays, radiation from the Van Allen belts, and electromagnetic energy is also present at high altitudes. This radiation has little effect on the properties of structural metals. However, semiconductors are sesitive to this type of radiation, since it produces changes in their crystal lattice structure. As a result, their electrical properties are permanently altered.

4. Simulation of the Space Environment

The simulation of the conditions that exist in outer space is a difficult undertaking because of the complexity of space and a lack of detailed knowledge concerning many of the space phenomena. However, to a large degree, the success of the space program depends on the ability to test materials, components, and entire systems under the expected operating conditions. The design and construction of space chambers is a major factor in the field of environmental testing. Numerous facilities have been constructed or are in the planning stage.

The lack of adequate test facilities and the inability to reproduce results at various locations have undoubtedly had a bearing on certain failures in the space program, i.e., failures in meeting the program objectives, rather than those associated with the launch and orbital phases of the mission. Many of the current problems are associated with surface effects. The emittance, reflectivity, adsorptance, and the tendency to cold weld depend on the physical properties of surfaces. These properties can be influenced by such space environment phenomena as thermal and penetrating radiation, ultrahigh vacuum, temperature extremes, etc. Three recent missions, OSO-1, OSO-2, and Mariner 4, have produced important data on coatings and have pointed out the difficulties in correlating space data with those derived from environmental testing. For example, in mission OSO-1 the thermal radiation properties of two coatings were measured under simulated conditions at two locations and in space. Neither the data obtained at the two test facilities agreed, nor did these individual data agree with those produced under space conditions. Similar results were obtained during the OSO-2 flight, although agreement on certain trends in the performance data was observed. Considerable improvement in data correlation was observed during the Mariner 4 flight. The observed surface temperatures were only a few degrees lower than predicted. The importance of data correlation was emphasized in a 1964 symposium devoted entirely to discussions on the thermal radiation of solids.[24] During the symposium, Gaumer stated that the most important means of ensuring reproducibility of data were to specify the surface completely in terms of material, surface preparation, coatings, etc.

Problems have also been experienced in predicting the behavior of surfaces in ultrahigh vacuum conditions. Fortunately, it is easier to duplicate these conditions (to a degree) than those which involve radiation sources. Some problems associated with adhesion and friction have already been cited. However, notable progress has been made in

establishing a good basis for the understanding of the mechanisms of adhesion and friction, and the problem now is to apply this knowledge wisely.

Numerous facilities to simulate certain aspects of the space environment have been designed and constructed by the National Aeronautics and Space Administration (NASA), the Air Force, and by space-oriented industrial firms. A partial listing of these facilities, together with their size and vacuum rating, is shown in Table VI.[11]

Table VI. Space Simulation Facilities[11]

Partial Listing

Location	Size (ft)	Vacuum (torr)
Jet Propulsion Labs	27 x 53	1×10^{-6}
General Electric	38½ x 30 (3)	1×10^{-8}
NASA, Goddard	35 x 60 (2)	1×10^{-8}
NASA, Houston	65 x 120 35 x 43	1×10^{-5} 1×10^{-4}
NASA, Langley	55 x 58	1×10^{-4}
Douglas	39 (spherical)	1×10^{-10}
Republic	13 x 24	1×10^{-8}
North American	15 x 28	1×10^{-8}
McDonnell	18 x 30	1×10^{-8}
Grumman	19 x 26	1×10^{-9}
Space Technology Labs	30 (spherical)	1×10^{-7}
RCA	20 x 26	5×10^{-6}

A space chamber is an assembly of subsystems(shell, vacuum system, thermal system, solar simulators, test and control equipment, and instrumentation). It would be desirable to simulate other features of the space environment, such as Van Allen belt and cosmic radiation, zero gravity, magnetic fields, and micrometeoriteparticles, but much remains to be done to fully understand these phenomena and develop suitable means to simulate them.

The facilities at NASA's Manned Spacecraft Center are an example of the advanced state of space simulation. The larger of the two test chambers at this location is 65 feet in diameter and 120 feet high. This chamber will accommodate a spacecraft having dimensions up to 75 feet high and 25 feet in diameter with a maximum base diameter of 40 feet. These chambers will provide the vacuum, thermal, and solar irradiation environment of space and the lunar surface. A combination of mechanical and diffusion pumps, plus 20 K cryopumping, will maintain a pressure of 10^{-5} torr under load (full-scale spacecraft plus two space-suited astronauts). Pumpdown time is estimated at 24 hours or less. The heat-sink characteristics of outer space will be simulated by a shroud of black, nitrogen-cooled panels. Carbon-arc solar simulators will irradiate the area with energy of the proper intensity and collimation. A variable-speed turntable will be provided to rotate the spacecraft as needed. The smaller of the two test chambers will be primarily used for astronaut training. It will be equipped to provide many of the features incorporated in the large chamber, but in a less sophisticated manner.

The design of vacuum systems and instrumentation for space chambers has been discussed by Hnilicka and Geiger[25] and by Latvala, Wang, and Mulkey.[26] All systems use a combination of methods to achieve the desired vacuum, since no single piece of equipment can handle the entire task. Mechanical pumps are used for "roughing" operations to reduce the chamber pressure to the range where diffusion pumps can be used efficiently. Significant advances in diffusion pump technology have extended the effective range of such equipment. Suitably trapped diffusion pumps can produce vacuums in the 10^{-8} to 10^{-10} torr range. Ion or ion-gettering pumps and cryogenic pumping techniques are needed to produce lower vacuums. Most modern large vacuum chambers can simulate altitudes of 100 to 300 miles (10^{-5} to 10^{-8} torr) without difficulty, and pressures corresponding to an altitude of about 1500 miles (10^{-12} torr) appear to be feasible. Pressures as low as 10^{-15} torr have been produced experimentally in a small chamber.

Accompanying these accomplishments in high-vacuum technology has been the development of suitable instrumentation to measure such low pressures. A variety of equipment has been designed to accomplish this objective, but as yet there is no practical answer to the problem of ultrahigh vacuum measurement that is accurate, simple, and inexpensive.

The technology of simulating secondary radiation, i.e., earth reflection and earth emission, was reported by Clauss[27] in connections with a program to provide such features for a large space chamber for the Arnold Engineering Development Center. The earth reflection (albedo) and earth emission intensity and spectrum are not completely defined since they depend on the cloud cover, terrain, and space vehicle position in the case of earth reflection. Because of the comparative size of the earth, it was not practical to duplicate secondary radiation with a single source. In this case, the required intensity of radiation was provided by tungsten filament lamps positioned around the chamber. Reflectors were used to confine the radiation to the desired spectrum.

Solar radiation for the test chamber was provided by carbon-arc solar simulators mounted on the outside of the carbon.[26] Of the available artificial radiation sources, the carbon-arc most closely resembles the spectrum of the sun. Because the carbon-arc is deficient in ultraviolet radiation, mercury lamps were used to fill in this portion of the spectrum. The design, operation features, and instrumentation of solar radiation sources are discussed by Norman.[28]

Section III. ADHESION PHENOMENA UNDER ATMOSPHERIC CONDITIONS

The basis for much of the current knowledge of the technology of metal-to-metal adhesion is associated with prior research on friction and wear conducted by those primarily interested in the science of lubrication. These phenomena were studied with the following objectives:

1) Determining the causes of friction and wear.
2) Developing theories of lubrication.
3) Minimizing the effects of friction and wear by effective lubrication.

Friction and wear have been investigated by others to determine their effect on the behavior of electrical contacts whose operation depends on sliding action. From the electrical standpoint, these phenomena are important because wear of contact surfaces affects the reliability of the contacts and introduces noise into low-level electrical circuits. Much of the research was prompted by the need to obtain better contact materials. More knowledge about adhesion was acquired with the development of the roll bonding and cold welding joining processes.

While it is impossible to cover all of these developments in detail, some of the important research will be summarized to indicate its impact on our knowledge of adhesion. As will be noted, the phenomenon of metallic adhesion is intimately associated with friction, and it is encountered in roll bonding or pressure welding, cold welding, and powder compacting. Unfortunately, each of these processes introduces variables which are difficult to control, and as such, tend to complicate explanations of the process of adhesion. An excellent review of solid-phase welding theories is provided by Milner and Rowe.[29]

1. Adhesion, Friction, and Wear

Although friction, wear, and related phenomena have been recognized for centuries, it is only since the early 1930's that they have been subjected to serious, scientific investigation. The research conducted at the University of Cambridge by Bowden[30] and his associates is the basis for the adhesive theory of friction. Because metal surfaces are not molecularly flat, the load between two sliding surfaces is supported by a number of highly localized contacts or asperities. These contacts deform plastically until their total area,

which is much less than the apparent contact area of the metal surfaces, will support the load. It was proposed that adhesion occurs at these contact points, and that friction arises from the shearing of these welds at a mean shear strength. The coefficient of friction was defined as the ratio of the frictional resistance (shear strength) to the load. For a given metal, the ratio of shear strength to yield pressure is almost constant, so the theory predicts a constant coefficient of fricition regardless of the load and the apparent area of the contacting surfaces. The coefficient of friction can be modified to account for a boundary lubricant or a contaminant film. Bowden's work indicated that the coefficient of friction between two sliding surfaces could be increased greatly if the surfaces were carefully cleaned. However, when surfaces were statically loaded, there was no appreciable resistance to separation in a direction normal to the interface, even when the surfaces were well cleaned. McFarlane and Tabor[31] noted that adhesion increased if, in addition to static loading, a slight tangential force was applied. Bowden and Rowe[32] confirmed this observation in adhesion studies conducted with outgassed gold, nickel, and silver. It was suggested that when a static load was applied normal to the interface, bonding occurred only at the asperities. When the load was released, the bonds were subjected to tension forces caused by the release of elastic stresses and many fractured. Thus, the adhesive strength was low. If a tangential or shear load was applied in addition to the load normal to the interface, the contact areas of the individual bonds increased and could support more stress when the applied loads were removed. Anderson[33] studied the influence of surface shear strains on the adhesion of metals; therefore, his data tended to confirm the adhesion theory of friction proposed by Bowden, et al. Anderson's data indicated that surface shear strains were necessary for adhesion to occur. They tended to remove surface contaminants, roughened the surfaces, and caused the metals to come into atomically close contact for bonding. Metallographic evidence was presented to show that surface contaminants were buried below the welded interface. On the basis of this research, Anderson and his coworkers developed a method to attach fine gold wire to semiconductor wafters.[4] A ball was formed at the end of a 0.003-inch diameter gold wire. Then the ball was positioned normal to the surface of a gold-plated semiconductor wafer and rotated until slippage indicated that adhesion had occurred.

In the course of studies to correlate adhesion with various physical and mechanical properties of metals, Sikorski[34] obtained data indicating the need for combined normal and tangential loading to produce bonding. Sikorski showed that metals with large elastic moduli, high

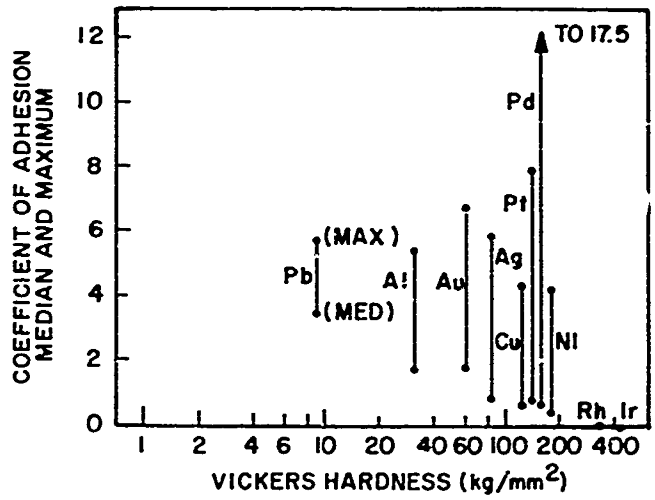
hardness, high surface energy, high recrystallization temperature, and high resistance to plastic flow have low coefficients of adhesion as do metals with a close-packed hexagonal structure. Statistical methods were used to derive a "median coefficient of adhesion," because the coefficient of adhesion was not reproducible from test to test. These data are shown in Figures 6 and 7. Sikorski also investigated the adhesion properties of several of the rare earth metals which, because of their crystal lattice structure, appear to be useful in applications where a minimum amount of adhesion is desirable.[35] Low adhesion properties are experienced with yttrium, gadolinium, dysprosium, and holium since all have close-packed hexagonal structures. Samarium, a metal with a rhombohedral structure also had a low coefficient of adhesion. The plastic flow properties of rhombohedral metals bear more resemblance to those of hexagonal close-packed metals than to those of cubic metals. Sikorski[35] also reviewed various methods of material selection to prevent adhesion.

Another theory of adhesion has been proposed by Semenov[2] and others. Semenov states that adhesion will occur even when perfectly clean metal surfaces are brought into intimate contact unless a "surface energy barrier" is overcome. This energy barrier is related to the necessity to redistribute surface atoms to form a grain boundary which is regarded as the criterion of weld formation.

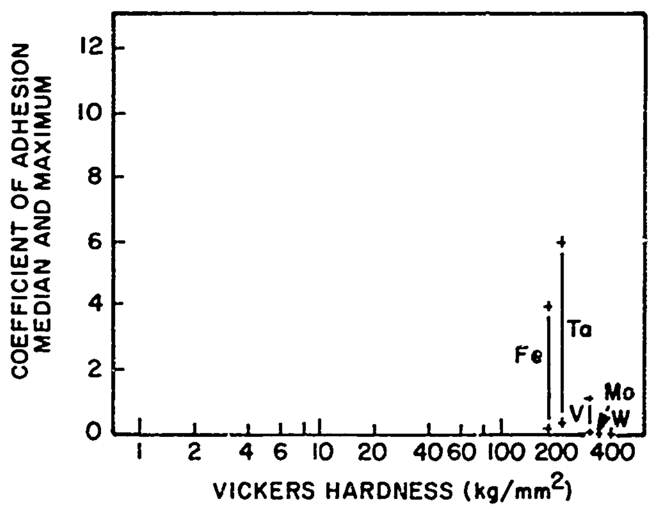
Additional research of interest on adhesion, friction, and wear has been reported by Burton, Russell, and Ku[36] (metallic friction at cryogenic temperatures), Mason[37] (effect of adhesion on fixed and sliding contacts), Rabinowicz and Tabor[38] (friction and metal transfer between sliding metal contacts), Goddard and Wilman[39] (derivation of theory of friction), Antler[40] (effect of friction and wear on electrical noise phenomena), and Furey[41] (surface temperatures during sliding contact).

2. Deformation or Pressure Welding

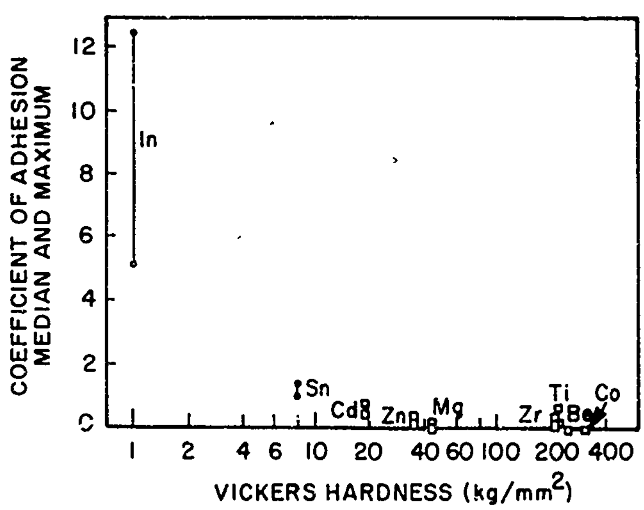
The work on deformation or pressure welding has contributed much to the understanding of adhesion phenomena. There are three well established methods of pressure welding: small-tool indentation welding, butt pressure welding, and roll bonding. Ultrasonic and friction welding are also methods of pressure welding. In all cases, deformation is used to break up oxides and other contaminants on metal surfaces to permit intimate metal-to-metal contact. The small-tool indentation welding and roll-bonding processes have received the most attention in recent years.



CORRELATION BETWEEN COEFFICIENTS OF ADHESION AND VICKERS HARDNESS FOR FACE-CENTERED CUBIC METALS.

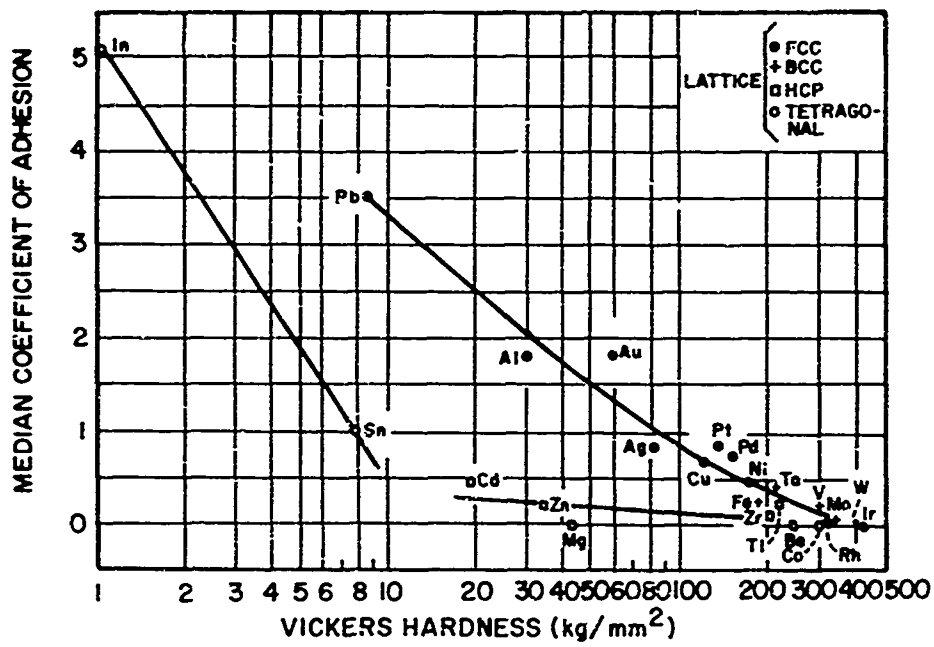


CORRELATION BETWEEN COEFFICIENTS OF ADHESION AND VICKERS HARDNESS FOR BODY-CENTERED CUBIC METALS.

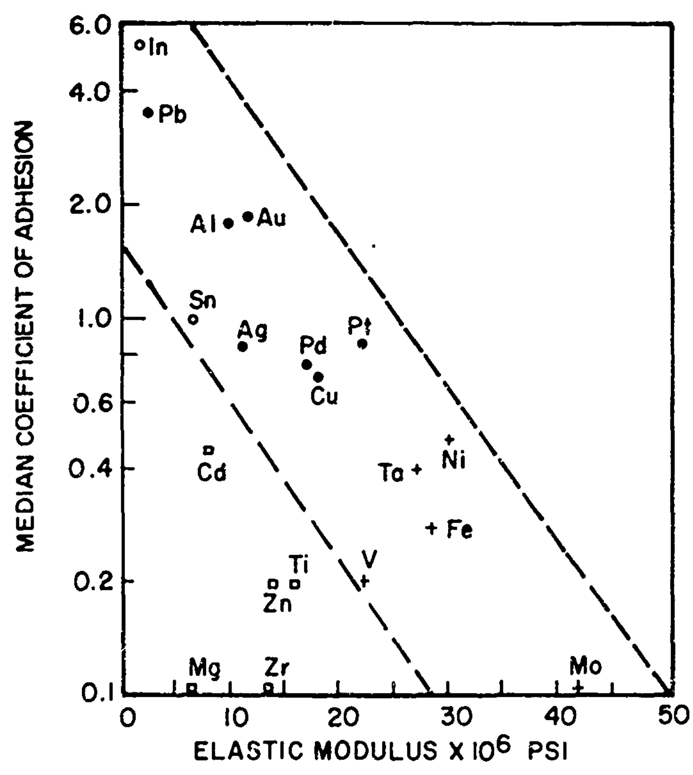


CORRELATION BETWEEN COEFFICIENTS OF ADHESION AND VICKERS HARDNESS FOR HEXAGONAL CLOSE-PACKED AND TETRAGONAL METALS.

Figure 6. Effect of Crystal Structure and Hardness on Coefficient of Adhesion[34]

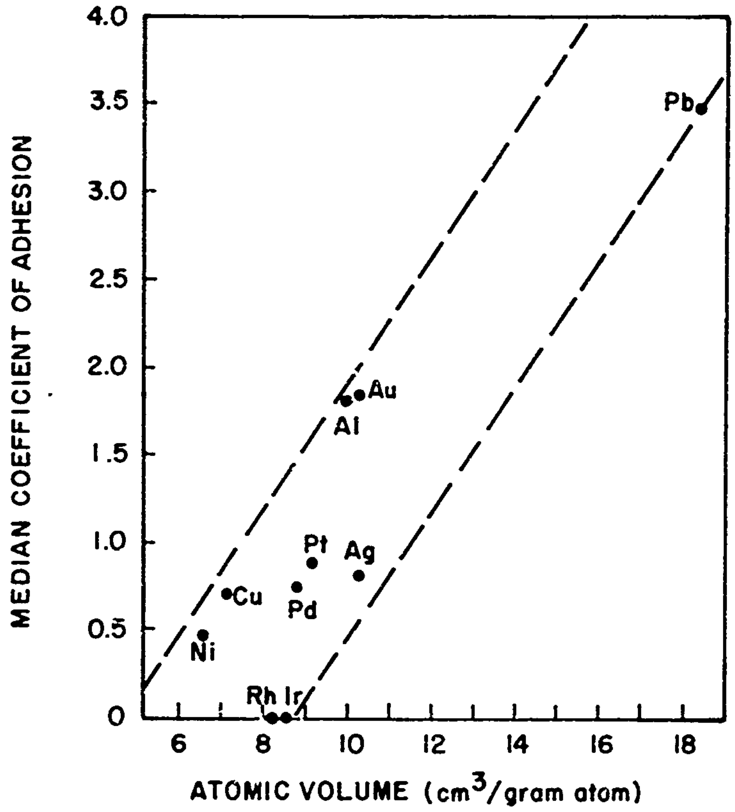


CORRELATION BETWEEN THE MEDIAN COEFFICIENTS OF ADHESION AND VICKERS HARDNESS FOR METALS OF VARIOUS LATTICE STRUCTURES.

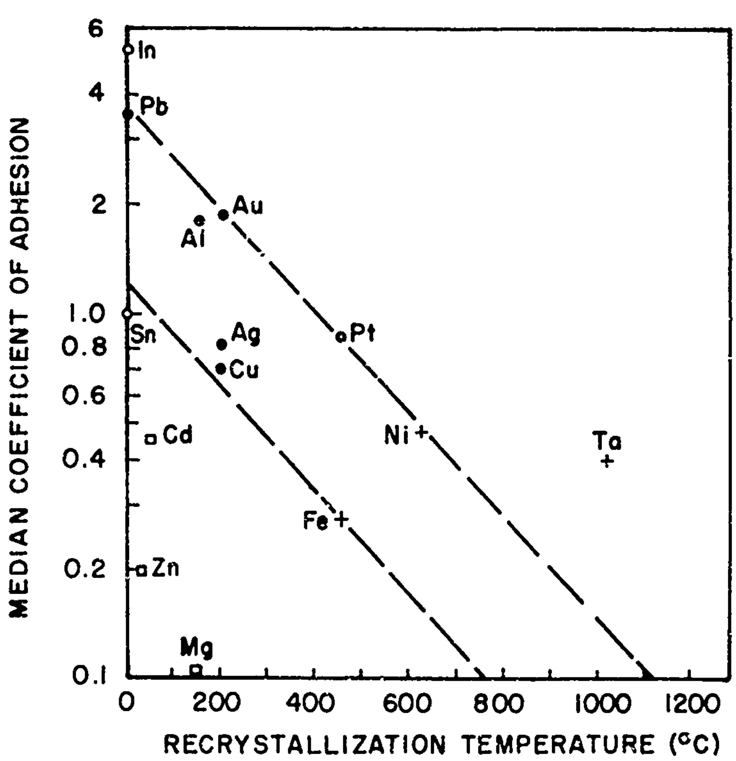


CORRELATION BETWEEN THE MEDIAN COEFFICIENT OF ADHESION AND ELASTIC MODULI FOR VARIOUS METALS

Figure 7. Effect of Physical Properties of Metals on Coefficient of Adhesion[34]



CORRELATION BETWEEN THE MEDIAN COEFFICIENT OF ADHESION AND ATOMIC VOLUME FOR FACE-CENTERED CUBIC METALS.



CORRELATION BETWEEN THE MEDIAN COEFFICIENTS OF ADHESION AND RECRYSTALLIZATION TEMPERATURES FOR METALS OF VARIOUS LATTICE STRUCTURES.

Figure 7. (Concluded)

Small-tool welds are made by overlapping the two pieces of metal to be welded and indenting them with a suitable punch which produces local deformation and welding at the interface. This is essentially the description of the cold welding process that has been exploited in the United States, Great Britain, and the Soviet Union. This process has been investigated most thoroughly in the Soviet Union. Some of the pertinent literature on cold welding is discussed briefly.

Following a brief discussion of the theories of cold welding, Baranov[42] discussed the uses of this process to produce lap and butt welds. Among the topics discussed were the preparation of surfaces for welding, the mechanics of the welding process, and the equipment available for welding. Specific data were presented for welding aluminum and copper-aluminum joints. In reviewing the state-of-the-art on cold welding, Khrenov[43] indicated that the following metals has been cold welded: aluminum, copper, silver, nickel, and titanium. Welds have also been made between such dissimilar metal combinations as aluminum to copper, and titanium to aluminum, copper, and steel.

There is considerable disagreement on the theory of cold welding as with other aspects of adhesion. Both the "surface film" theory and the "energy barrier" theory have been advanced to explain the mechanism of bonding. Aynbinder and Klokova[44] are advocates of the film theory, while Semenov[2] leans toward the energy barrier thesis.

Roll bonding is used industrially to produce clad metals and as a fabrication process to make heat-exchanger refrigerator panels and plate-type fuel elements. The plates to be joined are suitably cleaned, pinned or welded together to prevent movement during bonding, and rolled with or without preheating, depending on the metals being bonded. The dominant factors that control the roll bonding process are the presence of surface contaminants, retained elastic stresses, and the possible need to overcome an energy barrier. The work of Milner, et al, has contributed much to the understanding of the roll-bonding process, some features of which appear to be closely related to adhesion.

Vaidyanath, Nicholas, and Milner have investigated the mechanisms of roll bonding and the effect of surface preparation, surface contamination, roll pressure, time, and temperature on the strength of the welded joint.[45, 46, 47] With aluminum that was degreased and wire brushed, a 40-percent threshold deformation was required for bonding. Higher threshold deformations were required when the aluminum surfaces were either machined or wire brushed and then degreased. In

another study, Nicholas and Milner[48] investigated the roll bonding of tin, lead, zinc, aluminum, and copper. The threshold deformations required for welding are shown in Table VII. During the same study, aluminum, iron, magnesium, and zinc were roll bonded at room temperature and at elevated temperature. For aluminum, the threshold deformation decreased from 40 percent at room temperature to five percent at 1112°F. A weld strength equal to the base metal was obtained with Armco iron at 1652°F and 14-percent deformation. Very low weld strengths were obtained with zinc and magnesium bonded at room temperature and elevated temperature. It was presumed that these low strengths were associated with the strongly orientation-dependent behavior of the hexagonal metal structure that caused the oxides on the two surfaces to fracture independently of one another.

Table VII. Threshold Deformations for Room Temperature Deformation Welding[48]

Metal	Melting Point (°F)	Hardness, BHN		Threshold Deformation (%)
		Annealed	Cold-Worked	
Tin	450	5	6	15
Lead	621	4	4	10
Zinc	787	30	35	55
Aluminum (super purity)	1220	16	28	25
Aluminum (commercial purity)	-	20	40	40
Copper	1981	30	100	45

All of the research discussed above was conducted with similar metal couples, i.e., aluminum to aluminum, copper to copper, etc. McEwan and Milner[49] also investigated the roll bonding of dissimilar metal couples. Provided the temperature of rolling was sufficiently low to prevent diffusion, dissimilar metal couples weld in accordance with the rules developed to roll bond similar metals. Completely immiscible metals (Cd-Fe, Fe-Pb, Cu-Pb, and Cu-Mo) and those having a limited solubility (Cu-Fe, Cu-Ag, and Al-Zn) were successfully roll bonded. Subsequent heat treatment was sometimes needed to

improve the joint strength. Miscible metal pairs welded readily. With metal pairs that formed intermetallic compounds, the joint strength depended on the ductility and thickness of the intermetallic layer.

From the adhesion standpoint, the research on roll bonding is interesting. The same disagreement as to the mechanism of bonding exists for both processes. Difficulties were experienced in obtaining satisfactory joint strengths when metals with hexagonal crystal lattice structures were bonded. Low coefficients of adhesion have been obtained with metals of this type also. No particular difficulty was noted in bonding completely immiscible metals; such has not been the case in simple metal-to-metal adhesion.

During a program to investigate the use of ultrasonics for joining similar and dissimilar metals, a study of the fundamental mechanism of joining was conducted by Weare, et al.[50] Two mechanisms of bonding were suggested: pressure welding or fusion welding. These mechanisms may occur separately or simultaneously. In any case, ultrasonic energy provides the means to disrupt surface oxides, and it also produces the tangential or shearing forces needed for adhesion to occur. Using experimental and theoretical data obtained by Johnson[51] and Mindlin[52], respectively, equations relating the temperature of welding to the physical and mechanical properties of the metals were derived. The effect of shear forces during ultrasonic welding was investigated during a later program.[53]

Section IV. ADHESION AND FRICTION IN HIGH AND ULTRAHIGH VACUUM

Extensive research on adhesion, friction, and related subjects in vacuums simulating the conditions of outer space has been conducted in recent years. Since much of this research was prompted by problems associated with adhesion or cold welding in space, the major effort has been directed toward the prevention of adhesion and the development of suitable lubricants to minimize friction. Considering the urgency of these problems, this is understandable. However, research on the positive aspects of adhesion, i. e., the production of welds in space, is also required.

As the research is reported, it will be noted that the emphasis is on the fundamental aspects of adhesion and not on the development of practical design information. Thus, there are numerous studies on bonding selected metal couples, investigating the mechanism of adhesion, determining the effect of the physical properties of metals on adhesion, etc. However, the emphasis is shifting toward applied research. At least one friction experiment has been conducted in space and others are in the planning stages.

Most investigators who are studying the phenomena associated with metal-to-metal contact in the space environment refer to the adhesion or cohesion of metals under a particular set of experimental conditions. There is wide variance in such factors as the specimen design, method of surface preparation, method to achieve contact, environmental testing conditions, measurement of data, and the presentation of results. Each investigator is troubled by the difficulty in simulating space conditions, the lack of standardized specimens and procedures, and the objectives of his own particular program. As a result, there is little correlation between individual data, although considerable agreement in predicted trends can be observed. To cover the subject of adhesion in space adequately, it has been decided to discuss the research by company, university, or Government agency. Some organizations have pursued the subject of adhesion for several years in logically planned follow-on programs, while others have been engaged in numerous unrelated programs associated with adhesion, friction, lubrication, and the design and construction of equipment. The emphasis of this section is on studies concerned with bare metal-to-metal contact.

1. Fundamental Adhesion Studies

a. University of Cambridge

Some of the earliest research on adhesion and friction in a vacuum was conducted by Bowden[54] and his associates in 1951. A small vacuum chamber capable of maintaining the pressure at 10^{-6} torr was constructed. Equipment was also provided so the specimens could be heated during outgassing operations. The coefficient of friction of nickel, iron, platinum, and uranium couples was measured before and after outgassing in a vacuum. Significant increases in the coefficient of friction for all metal couples except uranium were noted. The effect of surface films of adsorbed gases on the coefficient of fric was studied also by admitting hydrogen, oxygen, and water vapor to the vacuum chamber. The presence of hydrogen had little effect on friction, but the presence of oxygen and water vapor produced surface films that decreased the coefficient of friction.

Bowden and Young[54] also studied friction phenomena with nonmetallic materials, since little research in this area had been undertaken. The coefficients of friction for graphite, carbon, and diamond were determined before and after outgassing in a vacuum.[55] As in the case of metals, the coefficient or friction increased sharply for graphite, carbon, and diamond when their surface films were removed by outgassing; however, the increase was small in comparison to that observed with metal couples. Again, the presence of oxygen or water vapor decreased the coefficient of friction.

b. Device Development Corporation

The adhesion of polished quartz crystals in an ultrahigh vacuum was reported by Smith and Gussenhoven.[56] Although it has been generally reported that the seizure of nonmetals does not occur (except for the case of cleaved mica sheets), the authors observed a strong adhesion between optically polished single-crystal quartz surfaces in a vacuum below 8×10^{-9} torr. If good quality optical flats are well cleaned and pressed together, they will adhere with a tensile strength of several kilograms per square centimeter . Adhesion is generally attributed to the surface tension of a thin film of adsorbed water between the surfaces. Experiments were conducted in a vacuum to eliminate the presence of an adsorbed film of water. Smith and Gussenhoven concluded that the observed adhesion was most likely due to Van der Waals forces, or more specifically, London dispersion forces; however, covalent or ionic bonding was not ruled out entirely.

c. Syracuse University

Keller and his associates have been studying the fundamental aspects of metal-to-metal adhesion since the early 1960's in programs sponsored by NASA. In 1961, Keller and Spalvins[57] reviewed and discussed the various theories of adhesion, and concluded that a theory relating the work of adhesion to the surface energies of the solids and the interfacial energy between them appeared to be most plausible. It was assumed that if the mechanism of adhesion could be thoroughly understood, the attractive forces could be reduced to a minimum by proper material selection, and as a result, wear could be minimized This approach to the process of perfect adhesion required contact between atomically clean surfaces. Equipment was designed and constructed to meet these requirements. The test chamber could be evacuated to 10^{-9} torr, and provisions to clean the specimens by ion and electron bombardment* were incorporated in the test chamber. A preliminary evaluation of the operation of the equipment was made with Fe-Al and Cu-Mo couples, and the specimen design was that of a hemisphere contacting a flat surface. Adhesion was observed with the Fe-Al couple but not with the Cu-Mo couple. Further research using this equipment was reported in 1962.[59] The following procedures were used during an adhesion test:

1) System bake-out at 450°C.
2) Filament degassing.
3) Argon ion bombardment to remove surface contaminants.
4) Electron bombardment to remove adsorbed argon from the metal surfaces.
5) Contact of specimens.
6) Measurement of adhesion and metallographic examination of the specimen surface.

Adhesion between the following soluble or partially soluble metal couples was observed: Fe-Al, Ag-Cu, Ni-Cu, and Ni-Mo. No adhesion was observed for the following immiscible metal couples: Cu-Mo, Ag-Mo, Ag-Fe, and Ag-Ni. These results generally paralleled those obtained

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*The ion bombardment process used by Keller to remove surface contaminants in a vacuum closely resembles the phenomenon of cathodic cleaning. Cathodic cleaning of a metal surface occurs during arc welding if the metal is at a negative potential with respect to the electrode and argon is used to shield the area. However, much higher voltages are needed under atmospheric condition. The principles of cathodic cleaning were reviewed by Pattee, Randall, and Martin[58] in a 1964 publication.

by other investigators in the field. No estimate of the adhesive strength was given. In 1964, Keller and Hauser[60] reviewed the research on adhesion and proposed that if an atomistic approach to the problem of adhesion was assumed, bonding between atomically clean surfaces would occur without the application of either normal or tangential forces.

In a dissertation published in 1964, Franklin[50] determined the surface energy of pure silver at 77K. Work of this type is needed to support the theoretical aspects of adhesion. In 1965, Keller[61] produced an excellent review of the state-of-the-art knowledge on adhesion phenomena.

In 1966, the role of surface contaminants in the mechanism of adhesion was reported by Franklin and Keller.[62] The equipment used in these studies is shown in Figures 8 and 9. Contact resistance measurements were made to indicate the occurrence of adhesion. These measurements could be converted to indicate the joint strength (adhesion) versus load. The effects of surface contaminants were investigated with an Ag-Ag couple and the following observations were made. Adhesion did not occur either before or after the bake-out cycle, indicating the presence of surface contaminants. However, significant adhesion was noted after these contaminants were removed by particle bombardment. After bombardment, adhesion was noted in a partial pressure of argon and in ultrahigh vacuum (10^{-9} torr). Adhesion occurred even when dry air was admitted to the system, but the joint strength was negligible. Adhesion did not occur in the presence of undried air. During these studies, adhesion was observed with the following metal couples: Ag-Ag, Cu-Ni (mutually soluble), and Ag-Ni (mutually insoluble). The observance of adhesion between immiscible metals contradicts previous experimental work by other investigators. These experimental studies were expanded to include an investigation of the adhesion of hard metals, since it is known that hard metals do not cold weld as easily as soft metals. Studies were conducted with the following metals pairs: Mo-Mo, Ti-Ti, and W-W.[63] Titanium was studied because of its intermediate hardness between that of the refractory metals and that of metals included in earlier studies; also, titanium has a hexagonal crystal lattice structure. To date, adhesion has been noted only with the Ti-Ti couple. A tendency toward adhesion was observed with the Mo-Mo couple. This report also contains a discussion of the interpretation of metallic adhesion data by Keller and Saunders, and the use of contact resistance measurements to indicate adhesion is explained in detail.

Contact resistance measurements have been used by Franklin and Keller[62] and Anderson[33] to indicate the occurrence of adhesion. Anderson, for example, noted that the contact resistance dropped about

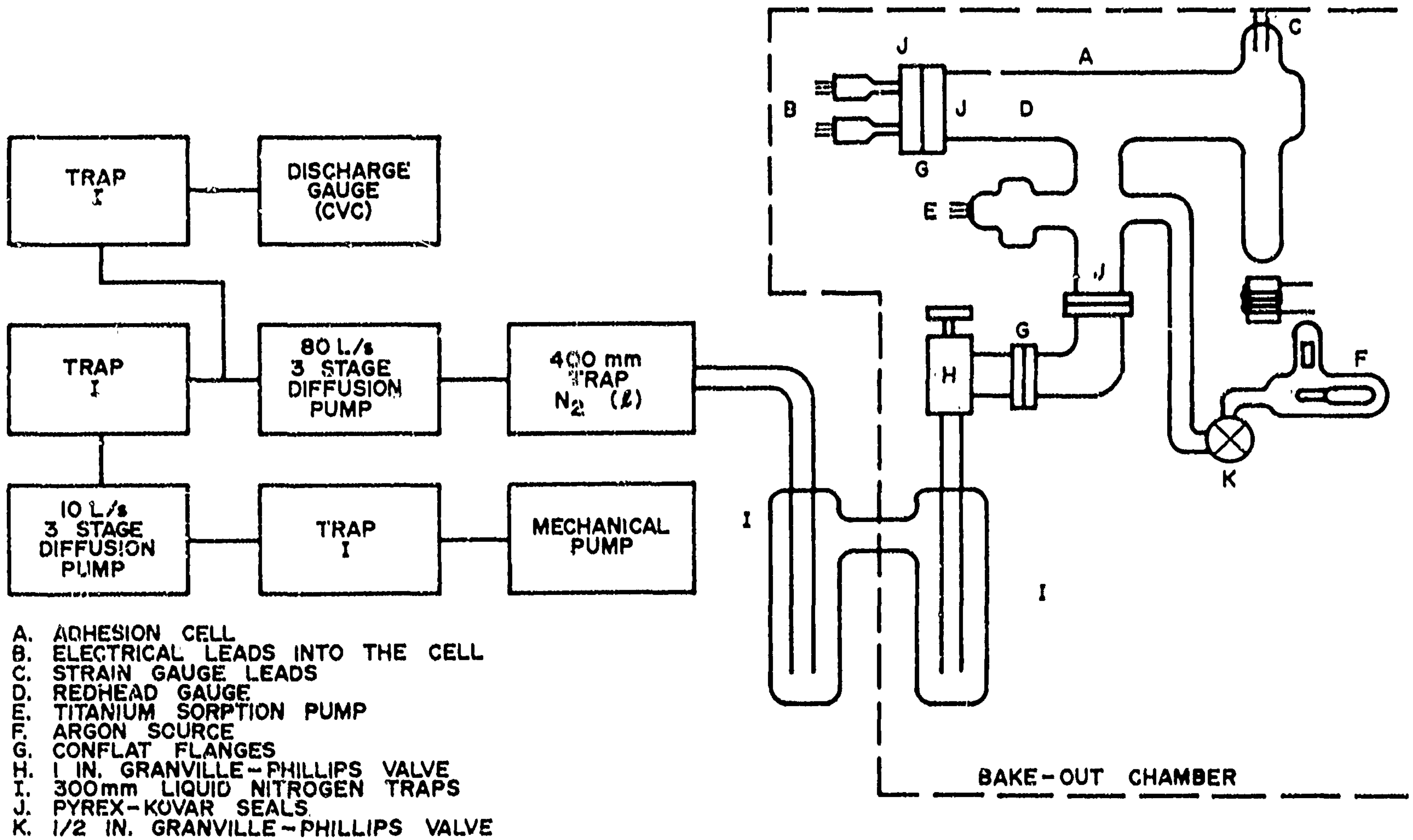


Figure 8. Sketch of Vacuum System[62]

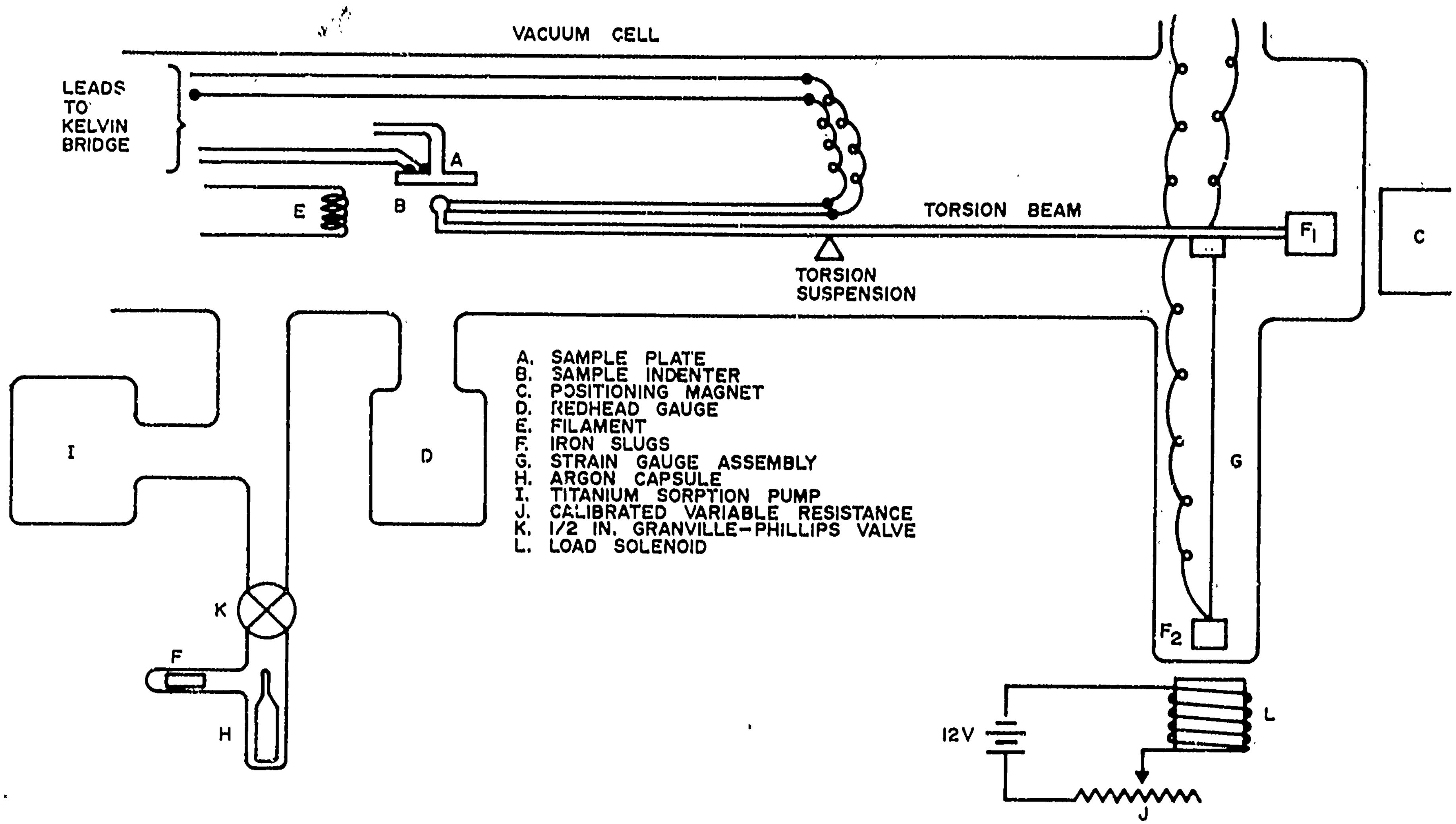


Figure 9. Sketch of Adhesion Cell[62]

an order of magnitude when adhesion occurred. The variation in contact resistance as a function of contact force for a metal couple where adhesion occurred is shown in Figure 10. After contact, the contact resistance decreased gradually until adhesion occurred; then, the resistance remained almost constant regardless of load. The contact resistance remained constant as the load was decreased, indicating that the two metals were still joined. A reverse load was required to fracture the joint. The relation between contact resistance and load for a metal couple where adhesion did not occur is shown in Figure 11. For this case, the contact resistance did not decrease until relatively high loads were applied to the metal couple. Also, as the load was decreased, the contact resistance increased gradually to the original value, rather than remaining constant as noted in Figure 10. Thus, nonadhesion of the metal couple was indicated. The variation in contact resistance can also be used to show the effects of surface contaminants on the occurrence of adhesion (Figure 12). The contact resistance can also be used to estimate the joint strength. For such calculations it is necessary to use the contact resistance data to estimate the contact area in the manner suggested by Holm.[64]

In 1966, a program on sessile-drop study of liquid-solid adhesion was sponsored by the Sandia Corporation.[65] Also, in 1966, Keller discussed the application of recent static friction data to the Adhesion Theory of Friction.[66]

d. NASA (Lewis Research Center)

Detailed research on friction and wear has been conducted by the Lewis Research Center since the early 1960's. While the research is directed toward the study of friction and wear from the lubrication standpoint, it should be reviewed because of the dependence of friction on adhesion. Buckley, Johnson, and their associates have investigated friction and wear as these phenomena are affected by ultrahigh vacuum conditions and the physical properties of the metals being studied. While this research is too extensive to be covered in detail here, the scope of the work will be outlined and important conclusions will be discussed.

The latest version of the vacuum friction and wear apparatus is shown in Figure 13.[67] The first unit was designed and constructed about five years ago and has been modified on numerous occasions to improve its performance; however, the basic concept of a rider contacting a rotating disk has been preserved. Friction and wear could be studied in a vacuum of 10^{-9} torr with the original equipment. The equipment shown in Figure 13 can maintain vacuums of about 10^{-11} torr. The

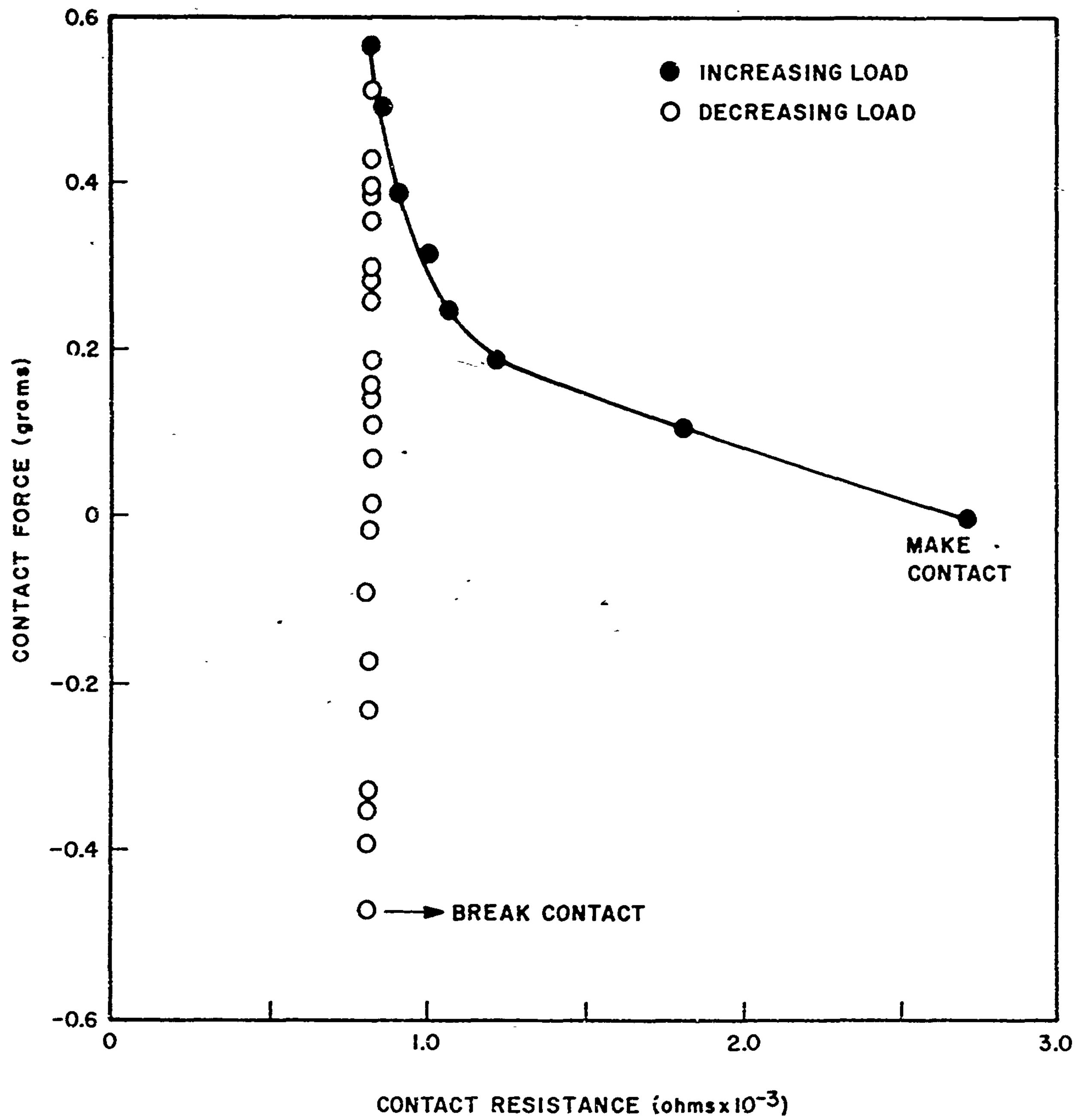


Figure 10. Variation of Contact Resistance with Load (Adhesion)[63]

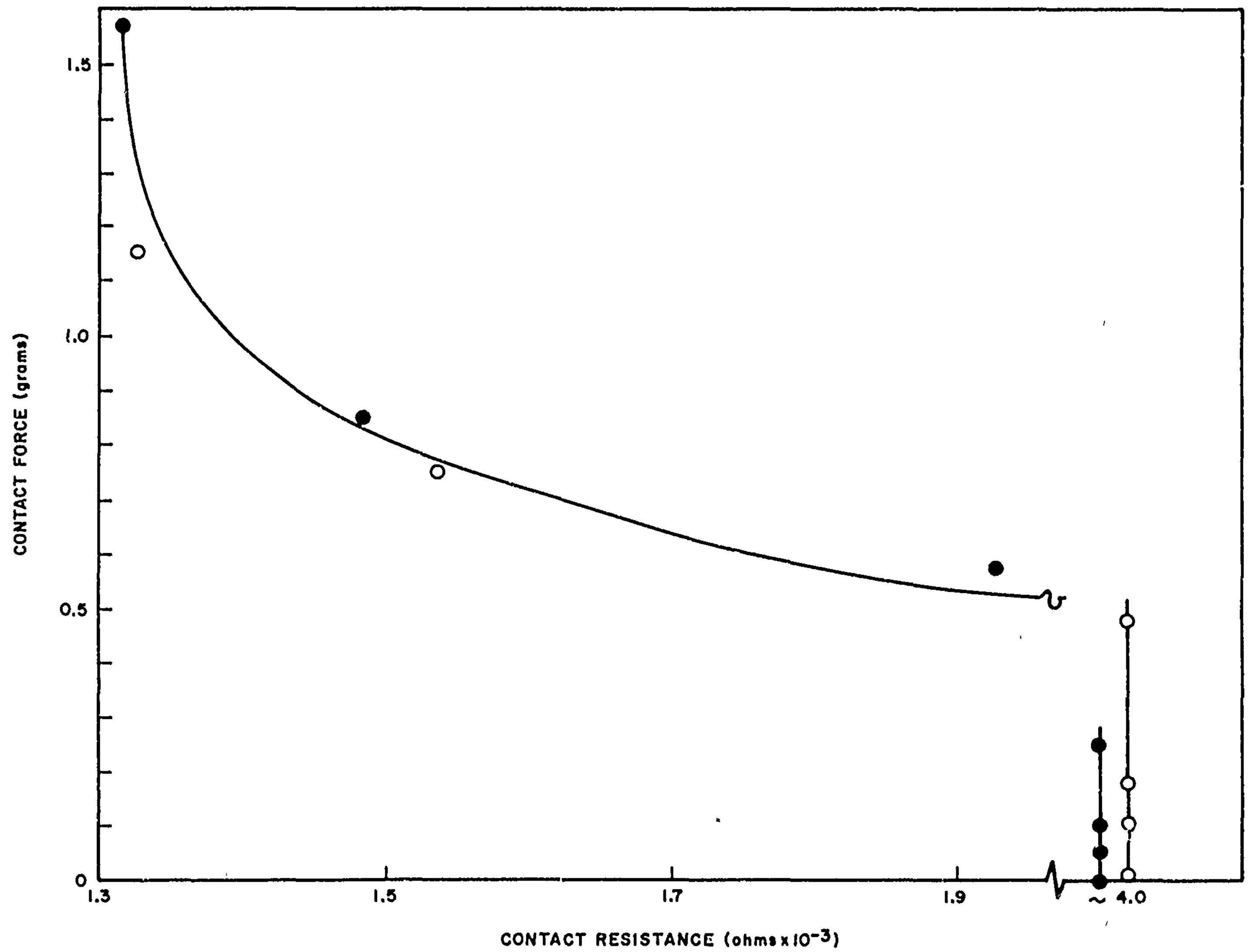


Figure 11. Variation of Contact Resistance with Load (Nonadhesion)[63]

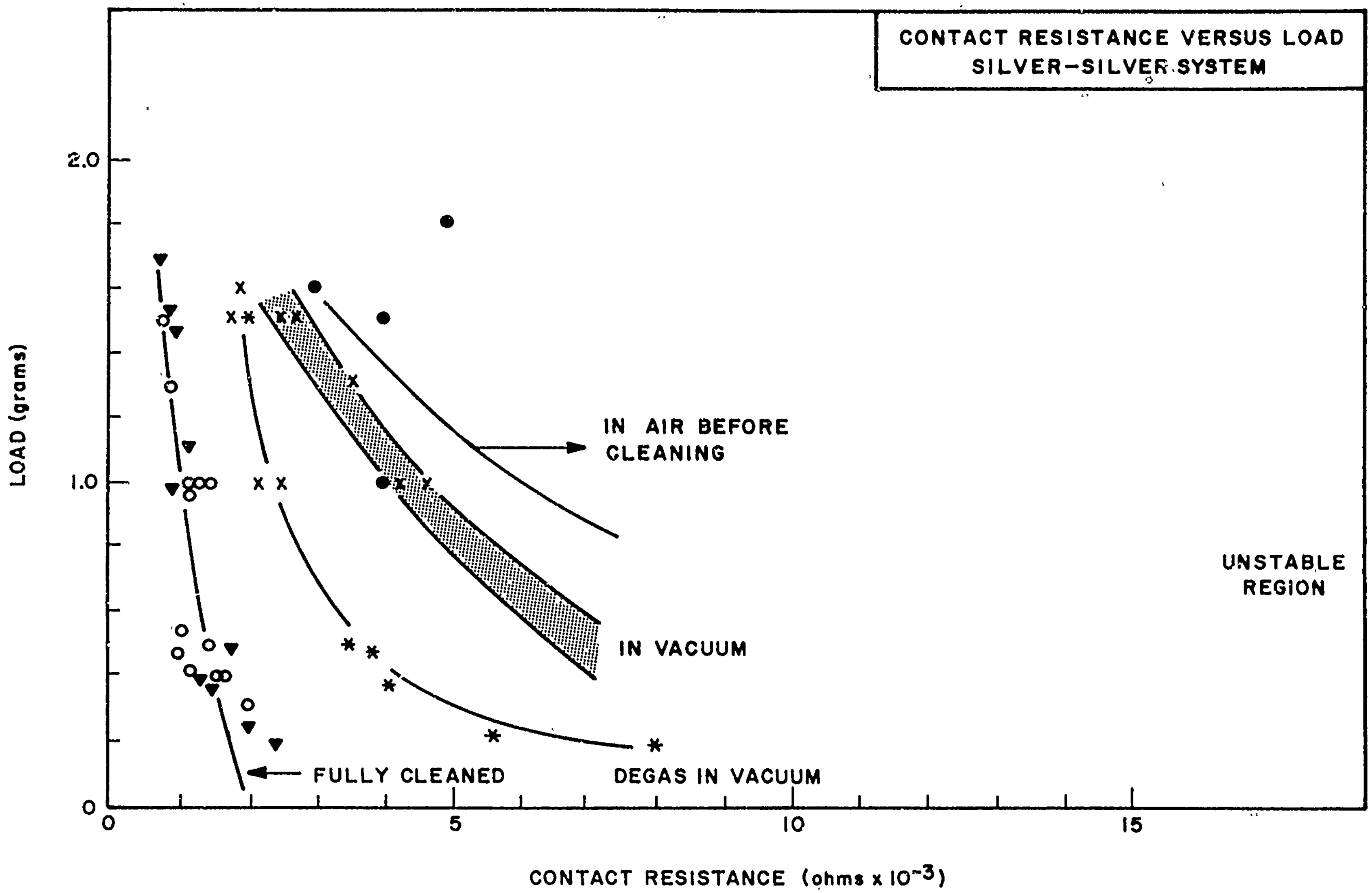


Figure 12. Effect of Surface Condition on Variation of Contact Resistance with Load[63]

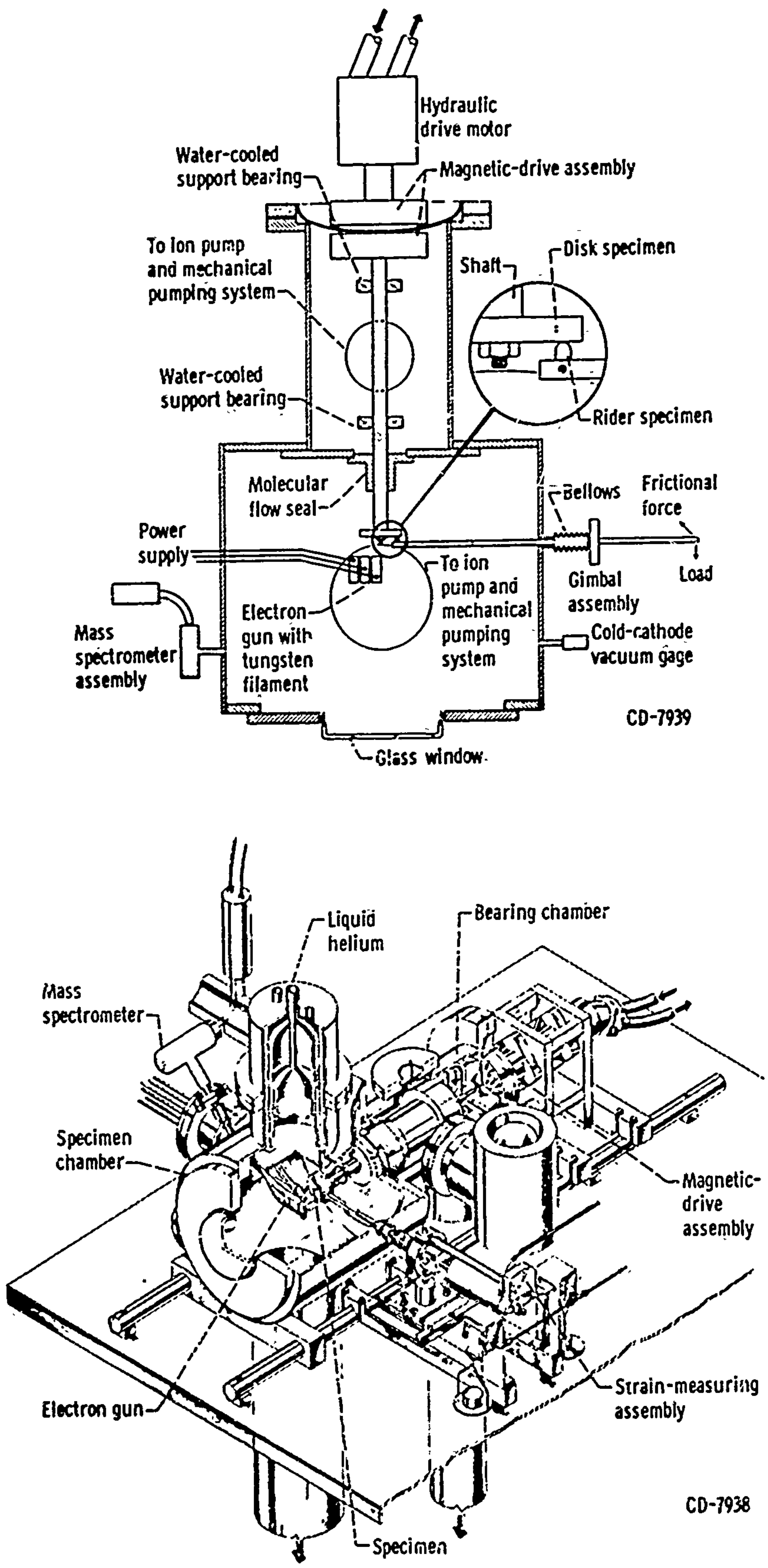


Figure 13. Ultrahigh Vacuum Friction Apparatus[67]

apparatus has two chambers, the bearing chamber and the specimen chamber, both of which are connected to the forepumping system. The forepumping section consists of a cold trap that is connected to two mechanical pumps. The specimen chamber is provided with an ion pump as well as cryopumping surfaces and the bearing chamber is also equipped with an ion pump plus a titanium sublimation pump. Both chambers are bakable. Other features of the equipment are evident in the illustration.

The details of individual research programs are discussed in the following paragraphs.

In 1962, Buckley, Swikert, and Johnson reported on a study of the friction, wear, and evaporation rates of metals and lubricants in a vacuum of 10^{-7} torr.[68] It was concluded that epoxy-phenolic and silicon resin bonded MoS_2 coatings provided effective lubrication for stainless steel. Thin coatings (0.0004-inch thick) of silver, lead, tin, and gold applied to Type 440 C stainless steel reduced the friction and wear normally encountered with this alloy in a vacuum. A mass transfer wear mechanism, unlike that encountered in air, was observed during the friction and wear studies. The evaporation rates for silver, gallium, cadmium, zinc, lead, tin, and magnesium were obtained under vacuum conditions at temperatures varying from room temperature to 1000°F.

Buckley and Johnson[69] studied the use of gallium-rich films as lubricants in air and in vacuum to 10^{-9} torr. Gallium was not equally effective as a lubricant for all materials. A diffused gallium-rich film reduced friction and wear when used with 52100 steel and 440 C stainless steel. The film was ineffective with the nickel-base and cobalt-base alloys studied. The friction and wear of gallium-coated substrates were lower in a vacuum than in air.

In 1963, Buckley and Johnson discussed the effect of microstructural inclusions on the friction and wear properties of electrolytic nickel and iron.[70] Additions of 1.35 to 7.5-percent nickel oxide to electrolytic nickel reduced friction and wear in a vacuum to the levels usually encountered in air. Wear and friction under vacuum conditions were reduced by a factor of 10 when tin (up to 20 percent) was added to electrolytic nickel. A reduction in friction and wear was also noted when sulfur in the form of an iron-sulfur alloy was added to electrolytic iron.

Studies of the effect of crystal structure on the friction and wear characteristics of cobalt and cobalt-base alloys were conducted in a vacuum of 10^{-10} torr.[71, 72] The crystal structure of cobalt transforms from close-packed hexagonal to face-centered cubic at 734° to 800°F.

During this investigation, transformation was controlled by varying the sliding speed and the ambient temperature. The research indicated that less friction, wear, and metal transfer occurred with the hexagonal form of cobalt than with the face-centered cubic form. Minimum friction was obtained with hexagonal cobalt against hexagonal cobalt. Maximum friction occurred with face-centered cubic cobalt against face-centered cubic cobalt. From the aspect of crystal lattice structure, these friction data are similar to adhesion data obtained by other investigators, since it has been recognized that metals having a hexagonal crystal structure do not bond readily. For single-crystal cobalt, less friction was observed when the crystal was oriented with the 0001 plane parallel to the direction of sliding, than when the 1100 plane was so oriented. The addition of 25-percent molybdenum to cobalt inhibited transformation from the hexagonal to the cubic form. Low friction values were obtained over a greater range of sliding velocities with this alloy than with pure cobalt.

Further research on the effect of crystal lattice structure on friction and wear was undertaken by Buckley and Johnson[73] with the rare-earth metals; data were obtained in a vacuum of 10^{-10} torr. As shown in Figure 14, many of the rare-earth and related metals undergo crystal

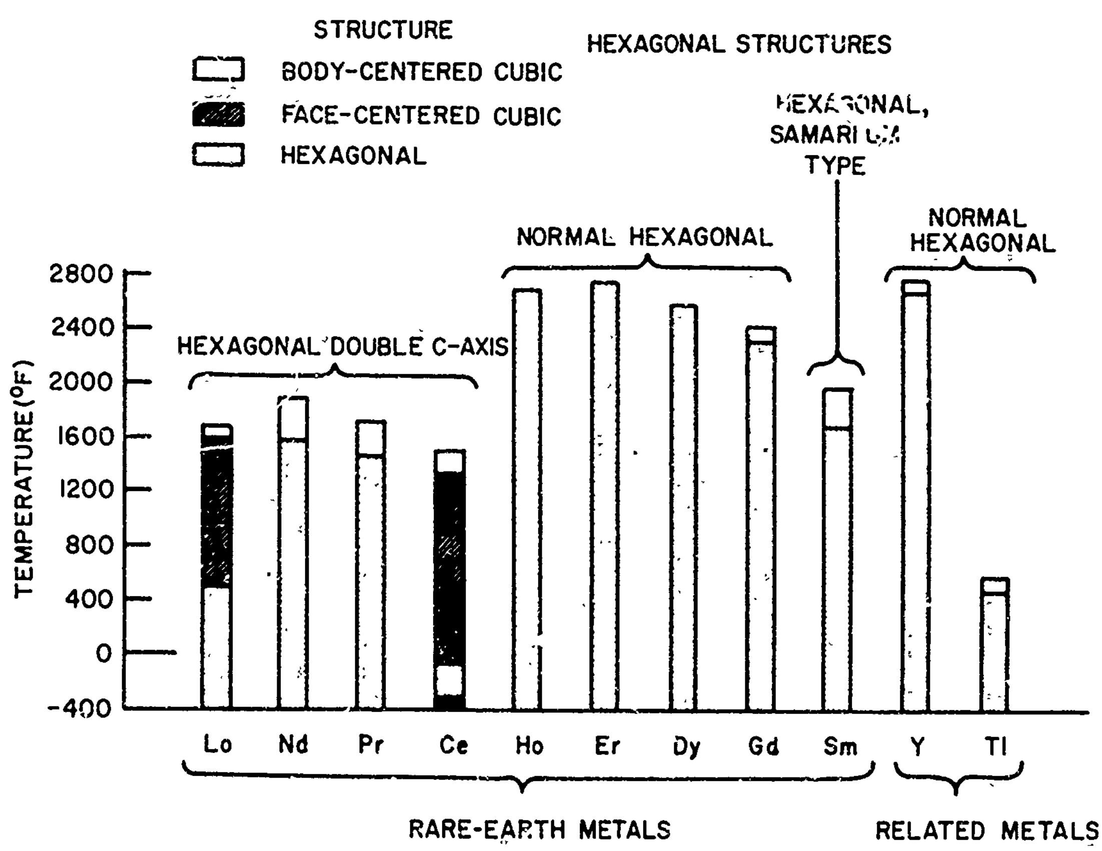


Figure 14. Crystal Transformations Indicated in the Literature for Rare-Earth and Related Metals[73]

transformation. The results indicated that the hexagonal crystalline phase of the rare-earth metals and thallium exhibited much lower friction, wear, and metal transfer characteristics than did the face-centered or body-centered phases of these metals. The crystal transformation of some of these metals, such as lanthanum, could be induced by varying the load, sliding velocity, or the ambient temperature (Figure 15). The crystal lattice structure of thallium is similar to those of the rare-earth metals. It has a hexagonal structure below 446°F and body-centered cubic structure above this temperature. Its friction properties are similar to those obtained with the rare-earth metals (Figure 16). The decrease in coefficient of friction at sliding velocities higher than 1000 feet per minute was attributed to melting of the thallium surface. The rare-earth metal friction data obtained under ultrahigh vacuum conditions should be compared with the adhesion data obtained by Sikorski[35] under atmospheric conditions.

Order-disorder transformations also had an effect on the friction properties of metals. In experiments conducted with copper-gold alloys, Buckley[74] noted an increase in the coefficient of friction with the transformation from an ordered to a disordered state. The effect of order-disorder transformation on the coefficient of friction, Young's modulus, and hot hardness of the Cu_3Au compound is shown in Figure 17. Similar behavior was observed with the CuAu compound.

The use of thin gold films to reduce friction was studied by Spalvins and Buckley.[67] A film of gold, 1800 Å thick, was vacuum-deposited on nickel and nickel-base metal substrates after electron bombardment. A marked improvement in the friction properties of these metals was attributed to the gold film acting as a lubricant.

e. <u>NASA (Ames Research Center)</u>

The effects of the following environmental conditions on the coefficient of adhesive of copper, silver, magnesium, titanium, zirconium, lead, 2024-T4 aluminum alloy, and tool steel were investigated at the Ames Research Center as follows:

1) Kind and quality of gaseous contaminants.
2) Exposure time.
3) Applied load.
4) Contact time.
5) Mechanical property changes during testing.[75]

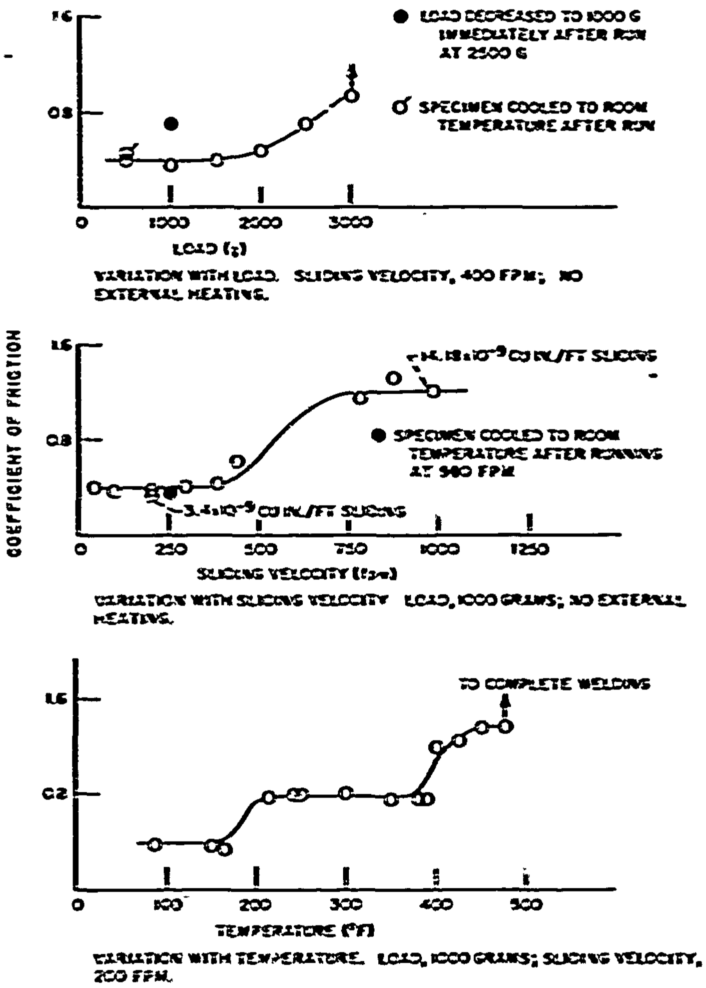


Figure 15. Coefficient of Friction of Lanthanium Sliding on 440 C Stainless Steel in Vacuum (10^{-9} mm Hg)[73]

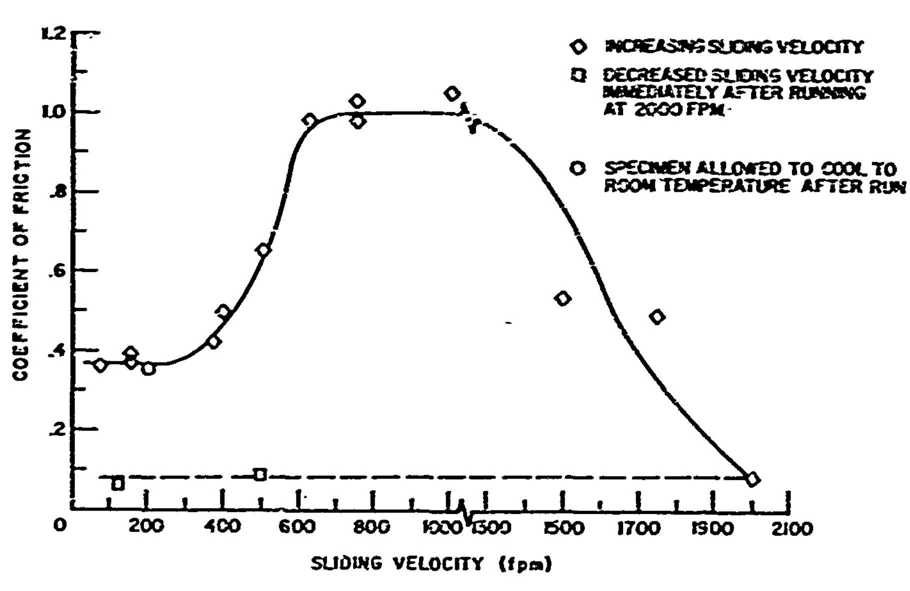


Figure 16. Coefficient of Friction for Thallium Sliding on 440 C Stainless Steel in Vacuum (10^{-9} mm Hg)[73]

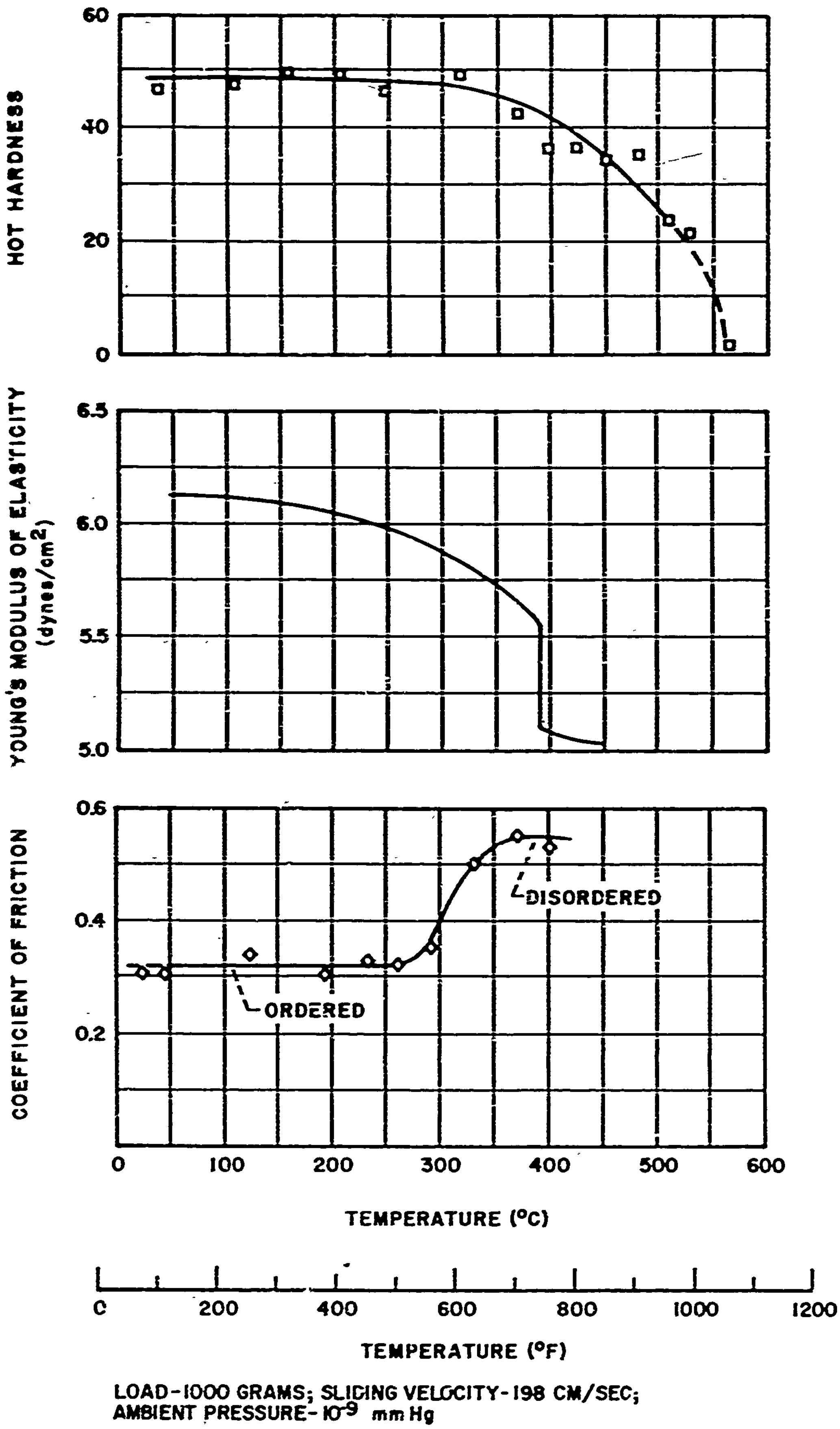


Figure 17. Hardness, Young's Modulus, and Coefficient of Friction for Cu_3Au (75 Atomic Percent Copper, 25 Percent Gold) Sliding on 440 C Stainless Steel at Various Temperatures[74]

A notched, cylindrical specimen (Figure 18) was repeatedly fractured and joined until the coefficient of adhesion was insignificant. The exposure time was the period during which the fractured surfaces were exposed to the chamber atmosphere. The effect of exposure time on the coefficient of adhesion for the various metal couples is shown in Figure 19. A gradual decrease in adhesion can be noted with the formation of a film of adsorbed gas, even in a vacuum of 5×10^{-8} torr. The effect of the chamber pressure and the presence of contaminating gases are shown in Figures 20 and 21, respectively. Only the presence of oxygen had any significant effect on the coefficient of adhesion, presumably because of chemisorption on the copper surface.

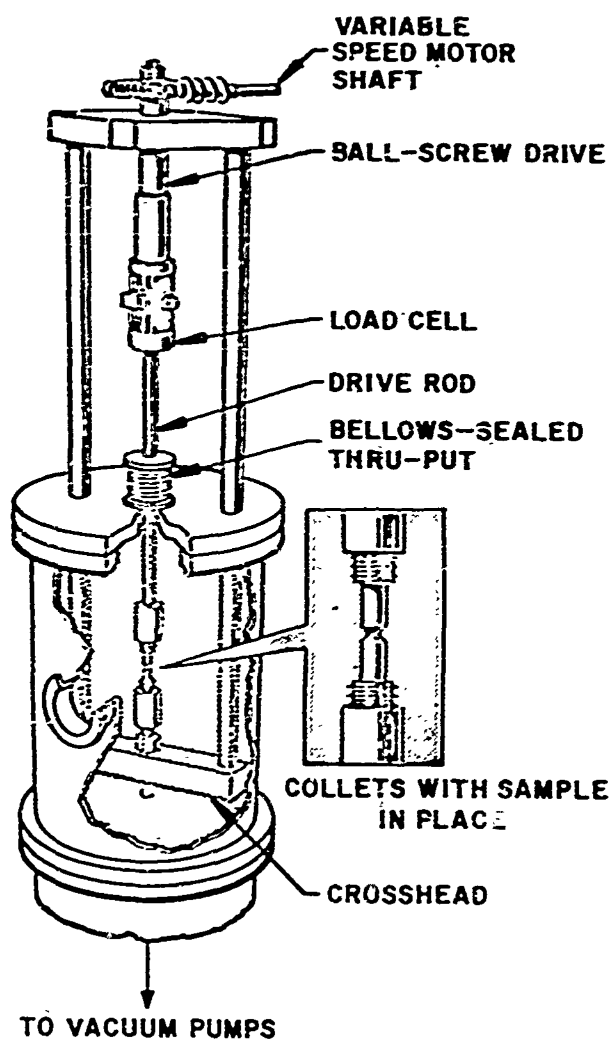


Figure 18. Schematic Diagram of Cold-Welding Test Apparatus[75]

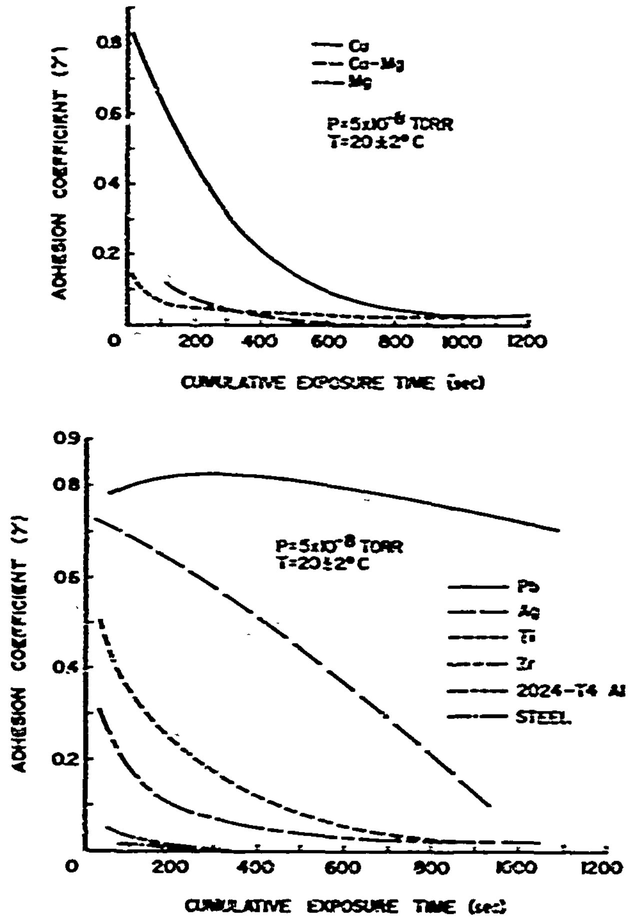


Figure 19. The Effect of Exposure Time on the Coefficient of Adhesion for Various Materials[75]

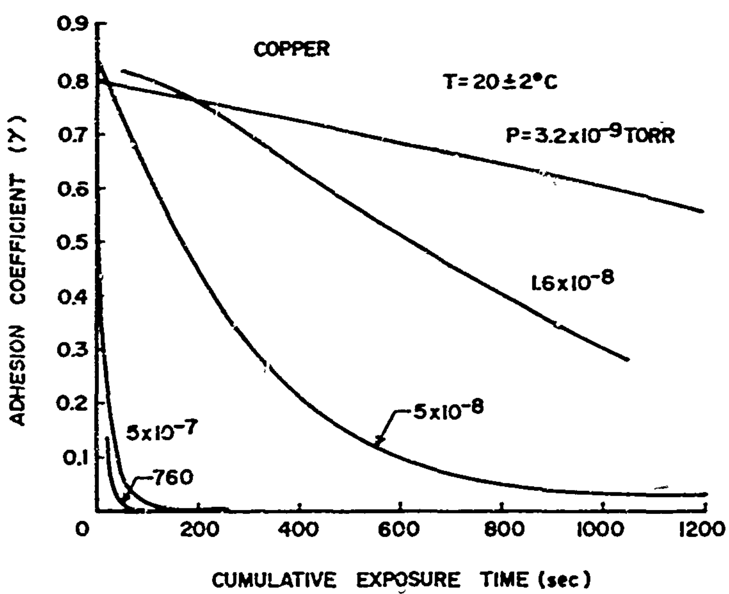


Figure 20. The Dependence on Pressure of the Coefficient of Adhesion for Copper[75]

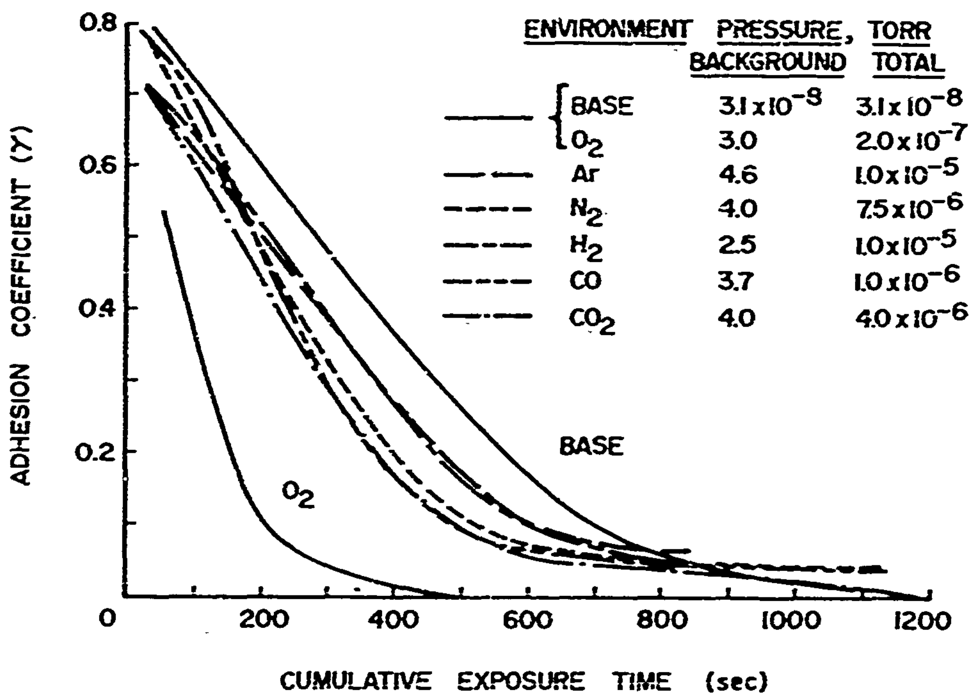


Figure 21. The Effect of Gaseous Environment on the Coefficient of Adhesion of Copper[75]

An empirical formula for the coefficient of adhesion was developed:

$$\text{coefficient of adhesion } (\gamma) = \frac{C\,(UTS)\,e_f}{H}$$

where UTS = ultimate tensile strength, kg/mm^2
e_f = elongation to fracture, mm/mm
H = Vickers hardness number, kg/mm^2
C = 4 (for best correlation with data).

The calculated coefficient of adhesion was compared with the experimentally determined coefficient of adhesion, and excellent correlation was obtained. Good agreement between these data and the coefficients of adhesion obtained by Sikorski[34] and Bowden and Rowe[30] was noted.

To prevent adhesion between metal couples, the investigators recommended the use of metals with high hardness and low ductility and the minimization of compression loads.

2. Applied Research

a. Hughes Aircraft Company

In early work at Hughes Aircraft, the effect of surface contaminants and the tendency for metals to seize or adhere were demonstrated in a vacuum of 2×10^{-9} torr.[76] A pointed rod of cold-rolled steel would not weld to a flat surface of the same material at room temperature, even after 75 days of exposure. However, if the rod was induction-heated to 1650°F and degassed for 1½ hours, immediate adhesion occurred on contact. The need for better vacuums was indicated when seizure did not occur again, one-half hour after the rod was heated and degassed.

Subsequent research was conducted for NASA over a period of two years. These studies were directed toward determining the effects of time, temperature, and environmental conditions on the adhesion or cohesion of metals.[77, 78, 79] In reporting the results of these investigations, Hughes Aircraft defined adhesion as the bonding of dissimilar metals, and cohesion was defined as the bonding of similar metals.

During the first year, equipment to accomplish the program objectives was designed and constructed, and static adhesion tests with selected structural metals and alloys were conducted. In static adhesion studies, the load was applied normal to the joint interface. In dynamic adhesion studies to be discussed later, a load combining normal and shearing forces was applied to the specimen. An environmental pressure of 5×10^{-9} torr or less was provided by the test chamber which also included equipment to heat and load the specimen. The specimens could be heated to temperatures of 25° to 500°C and axial loads up to 100,000 pounds per square inch could be applied. Equipment was provided to measure the compressive loads applied to the specimen and the tensile loads required to fracture the specimen. Breaking strengths as low as five pounds per square inch could be detected by the measuring equipment. The vacuum test chamber is shown in Figure 22.

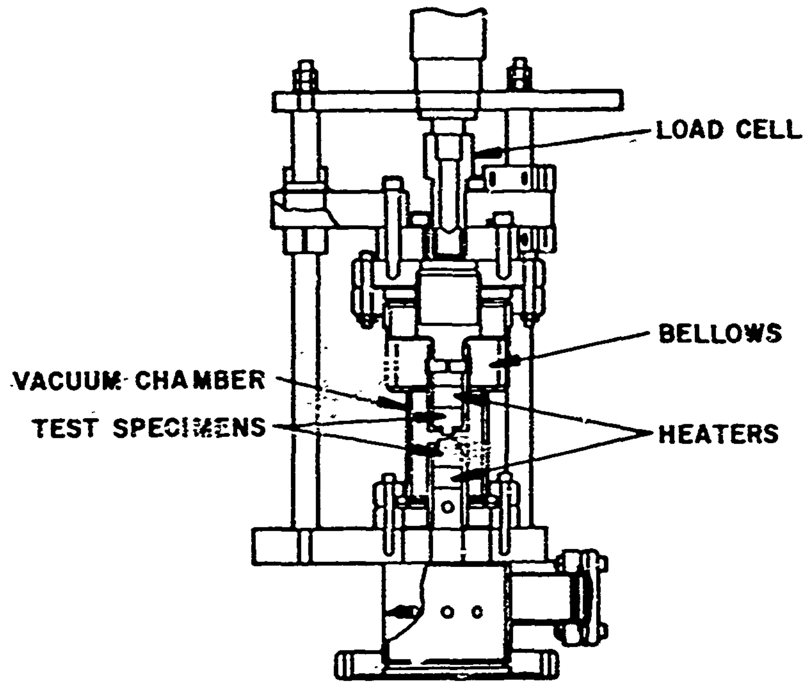


Figure 22. Static Adhesion Test Apparatus[77]

The effects of pressure, temperature, time, and load on the static adhesion properties of 16 different metal couples were determined. Compressive loads were limited to 80 percent of the compressive yield strength of the metal at temperature, 80 percent of the minimum load at which creep occurred, or 100,000 pounds per square inch, whichever was the lowest. Adhesion studies were conducted at 25°, 150°, 300°, and 500°C for all materials except aluminum. The maximum temperature for metal couples containing the aluminum alloy was 300°C. Before testing, the faying surfaces of the specimens were ground to a finish of 32 ±5 root mean square. After machining, the metal surfaces were cleaned by vapor degreasing in trichloroethylene.

Following surface preparation, the specimens were mounted in the vacuum test chamber in the separated position. The system was baked out at the desired temperature, and the chamber pressure and temperature were allowed to stabilize for six hours before testing commenced. During test, the selected load was applied for 10 seconds and then released, and the tensile force required to separate the specimens was then measured. If adhesion did not occur, the load was applied for successively long periods of 1000, 10,000, and 70,000 seconds (about 0.3 to 20 hours) or until measurable adhesion occurred.

The results of the static adhesion studies are summarized in Figure 23. The harder metals did not adhere under the conditions of

COUPLE	BOND STRENGTH (psi) 1000 2000	TEST CONDITIONS TEMP (°C)	LOAD (psi)	TIME (sec)	REMARKS
ANNEALED COPPER TO ANNEALED COPPER		150	5600	≤ 70,000	
		300	1800	≤ 10,000	
		300	1800	70,000	0.5% CREEP
	160	500	800	10	SUCCESSIVE TESTS OF SAME COUPLE
	30	500	800	100	
	370				
	1170	500	800	70,000	0.1% CREEP
2014-T6 Al TO 2014-T6 Al		150	64,600	≤ 70,000	CREEP STRENGTH EXCEEDED
		300	1410	≤ 70,000	
		300	2200	≤ 10,000	
	850	300	2950	70,000	
2014-T6 Al TO ANNEALED 304 STEEL		150	25,500	≤ 70,000	
		300	2940	≤ 10,000	
	445	350	2550	70,000	
2014-T6 Al TO A286 STEEL SOLUTION TREATED AND AGED		150	25,500	≤ 70,000	
		300	3440	≤ 10,000	
	80	400	3150	10,000	
2014-T6 Al TO Ti-6Al-4V SOLUTION TREATED AND AGED		150	[illegible]	≤ 70,000	
		300	5800	≤ 10,000	
		300	4050	70,000	CREEP STRENGTH EXCEEDED
	1735	300	5440	70,000	
2014-T6 Al TO ALLOY 41 SOLUTION TREATED AND AGED		150	25,500	≤ 70,000	
		300	2560	≤ 10,000	
	1750	300	3220	70,000	
ANNEALED 304 STEEL TO ANNEALED 304 STEEL		500	16,000	≤ 70,000	
ANNEALED 304 STEEL TO A286 STEEL SOLUTION TREATED AND AGED		500	16,000	≤ 70,000	
ANNEALED 304 STEEL TO Ti-6Al-4V SOLUTION TREATED AND AGED		500	16,000	≤ 70,000	
ANNEALED 304 STEEL TO ALLOY 41 SOLUTION TREATED AND AGED		500	16,000	≤ 70,000	
Ti-6Al-4V SOLUTION TREATED AND AGED TO Ti-6Al-4V SOLUTION TREATED AND AGED		150	80,500	≤ 70,000	
		300	65,000	≤ 70,000	
		500	29,000	≤ 70,000	CREEP STRENGTH EXCEEDED
Ti-6Al-4V SOLUTION TREATED AND AGED TO ALLOY 41 SOLUTION TREATED AND AGED		500	58,000	≤ 1000	
		375	58,000	≤ 70,000	
A286 STEEL SOLUTION TREATED AND AGED TO A286 STEEL SOLUTION TREATED AND AGED		500	67,000	≤ 70,000	
A286 STEEL SOLUTION TREATED AND AGED TO ALLOY 41 SOLUTION TREATED AND AGED		500	67,000	≤ 70,000	
ALLOY 41 SOLUTION TREATED AND AGED TO ALLOY 41 SOLUTION TREATED AND AGED		500	100,000	≤ 70,000	
17-4 PH STEEL H900 TO 17-4 PH STEEL H900		500	65,800	≤ 70,000	

Figure 23. Effect of Bonding Variables on Static Adhesion[77]

maximum severity; i.e., temperature--500°C, time--70,000 seconds, and maximum applied load. The following metal couples were included in this classification:

1) 304 steel/304 steel.
2) 304 steel/A286 steel.
3) 304 steel/Ti-6Al-4V
4) Ti-6Al-4V/Ti-6Al-4V.
5) 304 steel/René 41.
6) Ti-6Al-4V/René 41.
7) A286 steel/A286 steel.
8) A286 steel/René 41.
9) René 41/René 41.
10) 17-4 PH steel/17-4 PH steel.

It was assumed that these metal couples would not adhere under less severe conditions. Thus, these couples are suitable for use at altitudes corresponding to a pressure of 5×10^{-9} torr in static loading at temperatures up to 500°C and loads within their elastic limits.

The following metal couples did not bond at 150°C, but most of them bonded at 300°C:

1) Copper/copper.
2) 2014-T4/2014-T4.
3) 2014-T4/304 steel.
4) 2014-T4/A286 steel.
5) 2014-T4/René 41.
6) 2014-T4/Ti-6Al-4V.

These metal couples can be used in the space environment at temperatures of 150°C or less.

For the dynamic adhesion studies, the equipment in the test chamber was modified to impart an oscillatory motion to the upper test specimen; thus, the specimens were loaded by a combination of axial and tangential forces. The preliminary procedures used to condition the specimens for test were identical to those used in the static adhesion tests. During test, the specimens were loaded to 12.5 percent of the maximum load discussed earlier. Then, the upper specimen was oscillated ±2 degrees at three cycles per second for 10 seconds at room temperature. If adhesion did not occur under these conditions, additional tests were made at successively higher temperatures, higher loads, or longer periods of oscillatory motion. The results from the dynamic adhesion studies are shown in Figure 24. In Figure 25, the minimum conditions at which bonding occurred are compared with the conditions of maximum

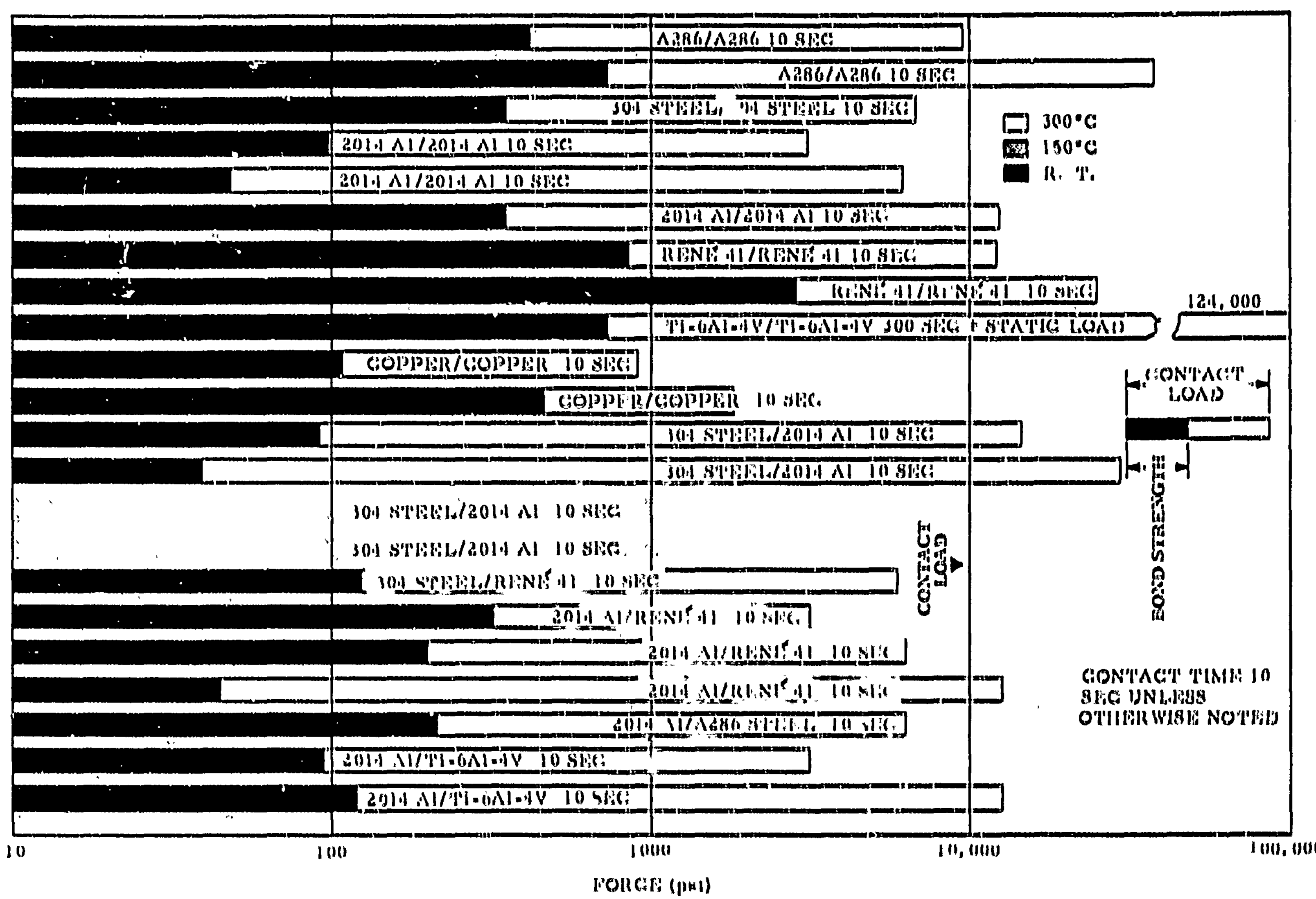


Figure 24. Effect of Bonding Variables on Dynamic Adhesion[78]

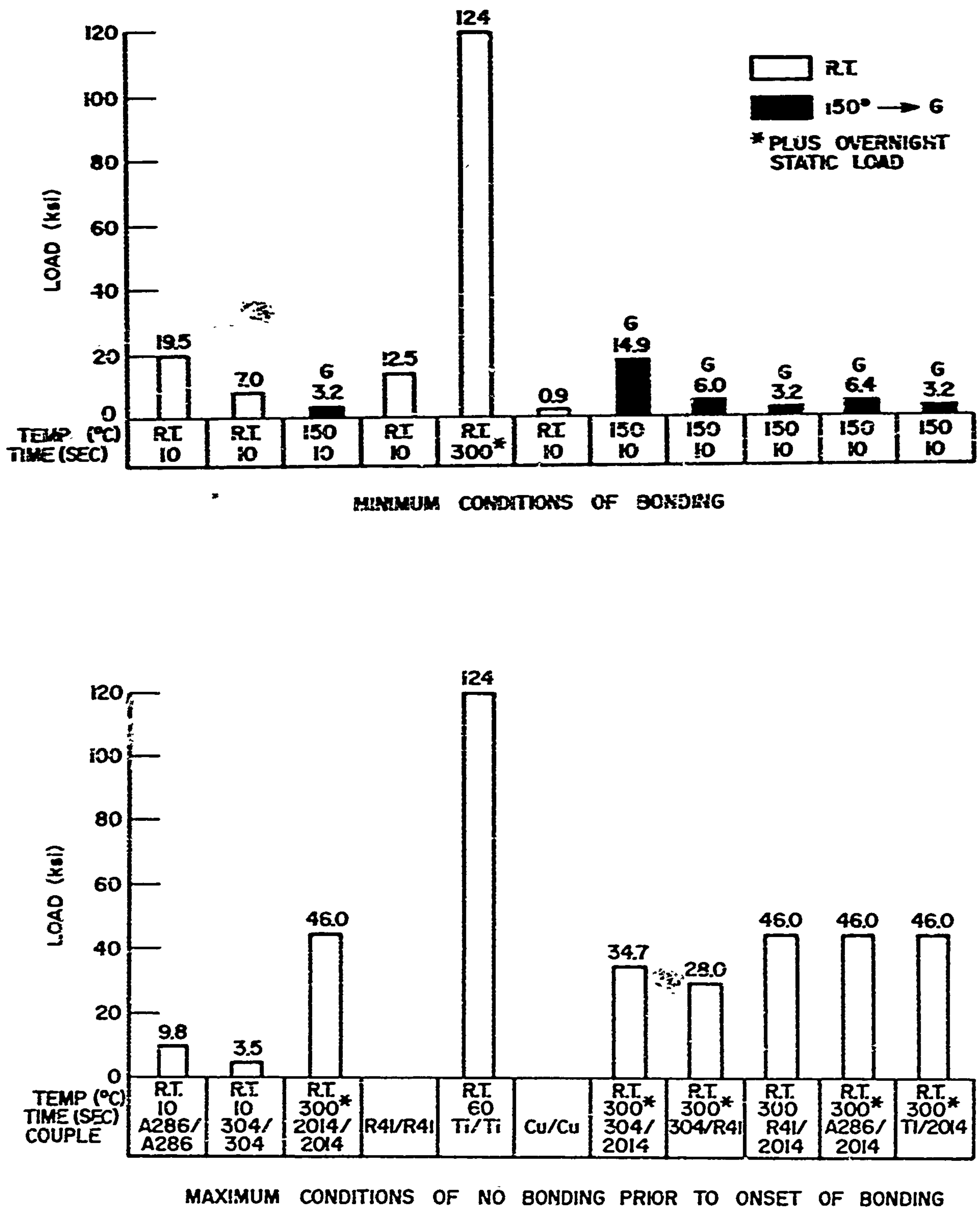


Figure 25. Effect of Dynamic Loading on Adhesion[78]

severity that did not produce bonding. It was assumed bonding would occur at loads higher than those which produced initial bonding.

All metal couples bonded at conditions within the prescribed limits, and at less severe conditions of time, temperature, and load than were needed for static adhesion. Some couples that did not bond during static tests at 500°C readily bonded at room temperature during the dynamic tests. This trend is in agreement with trends established by other investigators.

For operations in the space environment, the temperature limits to avoid adhesion under dynamic loading are shown in Table VIII. Metal couples that bonded at any load at a given temperature are not included in this summation. The results of the static and adhesion studies are shown in Figure 26.

Table VIII. Temperature Limits for Avoiding Adhesion[79]

No.	Couples	Conditions for No Adhesion (°C)	Conditions for Adhesion (°C)
1	Copper/Copper		25 and above
2	304 Steel/304 Steel		25 and above
3	2014 Aluminum/2014 Aluminum	25 and below	150 and above
4	2014 Aluminum/304 Steel	25 and below	150 and above
5	René 41/René 41		25 and above
6	René 41/2014 Aluminum	25 and below	150 and above
7	René 41/304 Steel	25 and below	150 and above
8	A286 Steel/A286 Steel		25 and above
9	A286 Steel/2014 Aluminum	25 and below	150 and above
10	Ti-6Al-4V/Ti-6Al-4V		25 and above
11	Ti-6Al-4V/2014 Aluminum	25 and below	150 and above

b. Midwest Research Institute

Programs to investigate adhesion under ultrahigh vacuum conditions have been conducted for NASA by Midwest Research Institute. In 1964 through 1965, the following aspects of high-vacuum technology were investigated:[80,81]

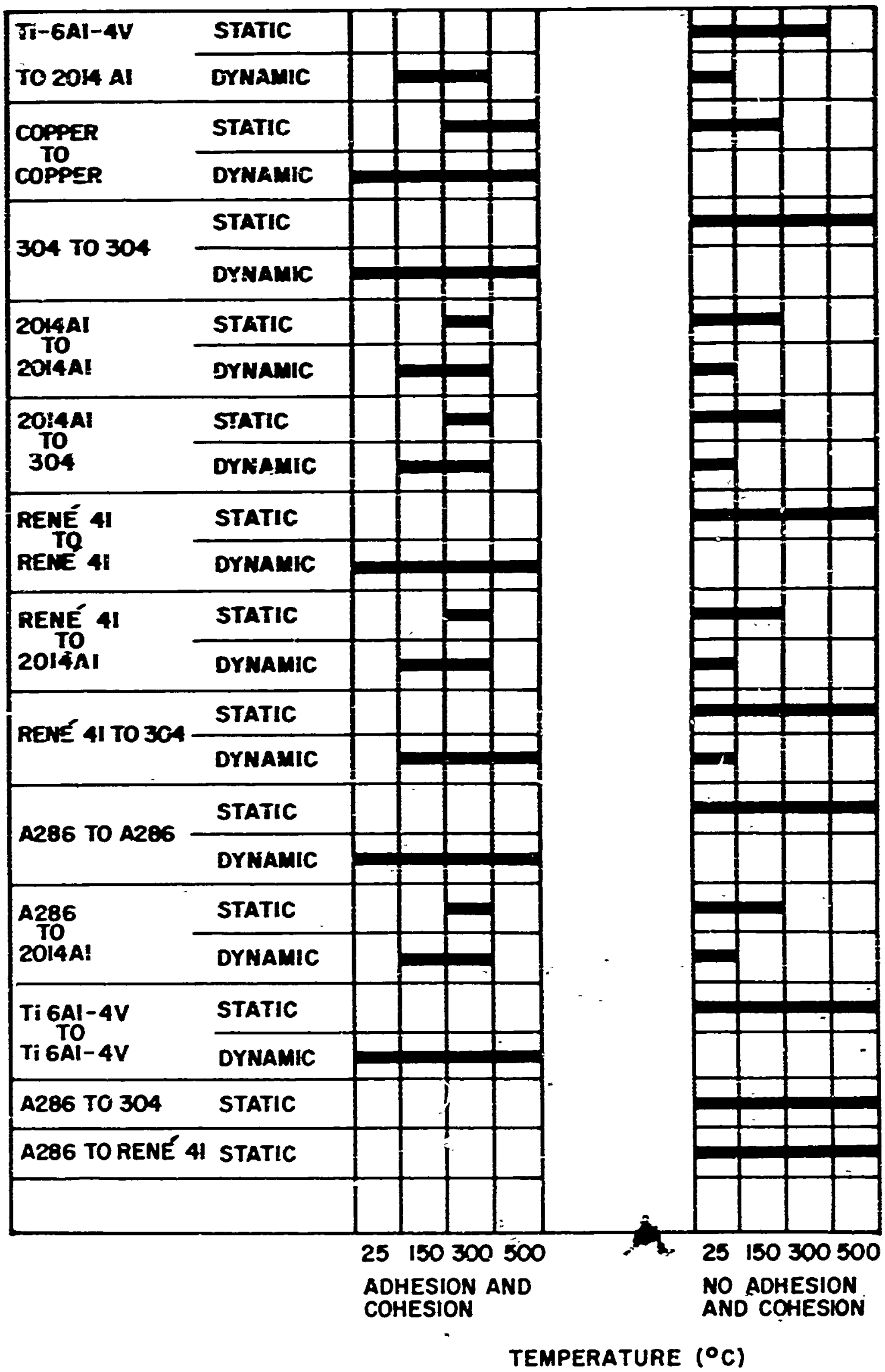


Figure 26. Comparison of Adhesion Under Static and Dynamic Conditions at Various Temperatures[77]

1) A cesium treatment for glass surfaces was developed to decrease permeation of the glass by helium.
2) The quantities and species of gas above getter-ion pumps and chemically trapped oil diffusion pumps were determined.
3) An adsorption isotherm for inert gases was developed for use in predicting the performance of cryogenic pumping surfaces.
4) Equipment to measure vacuums of 10^{-12} torr or less was evaluated and improved.
5) Preliminary adhesion studies with stainless steel, aluminum, and titanium alloys were conducted.

In 1965, the results of a study to determine the friction and adhesion properties of 45 metal couples in an ultrahigh vacuum were reported.[82] The following metals and alloys were tested against themselves and against each other:

1) 2014-T6 aluminum alloy.
2) Ti-6Al-4V titanium alloy.
3) Beryllium copper.
4) Electrolytic copper.
5) Cobalt.
6) Type 321 stainless steel.
7) René 41.
8) E-52100 steel.
9) Coin silver.

The test specimen assembly was exposed to a chamber pressure of 5×10^{-10} torr before contact was made. During the test, the chamber pressure was in the 10^{-9} torr range.

An outline drawing of the vacuum test chamber is shown in Figure 27. For determining the coefficient of friction with the various metal couples, the concept of three metal pellets resting or being rotated on an annular wear track was used. The pellets, 0.0625 inch in diameter, and the wear track, 2.3 inches in diameter, were machined from the selected metals, and were then lapped and polished to a finish of one μ root mean square or less. An enlarged view of the test specimen section of the vacuum chamber is shown in Figure 28. The pellets were weighted to produce a contact pressure of 1000 pounds per square inch and heaters were provided to maintain the wear surface temperature at 200°C. The coefficient of friction was determined by measuring the torque needed to rotate the pellets on the wear track. During the static test, the coefficient of friction was measured at breakaway after the

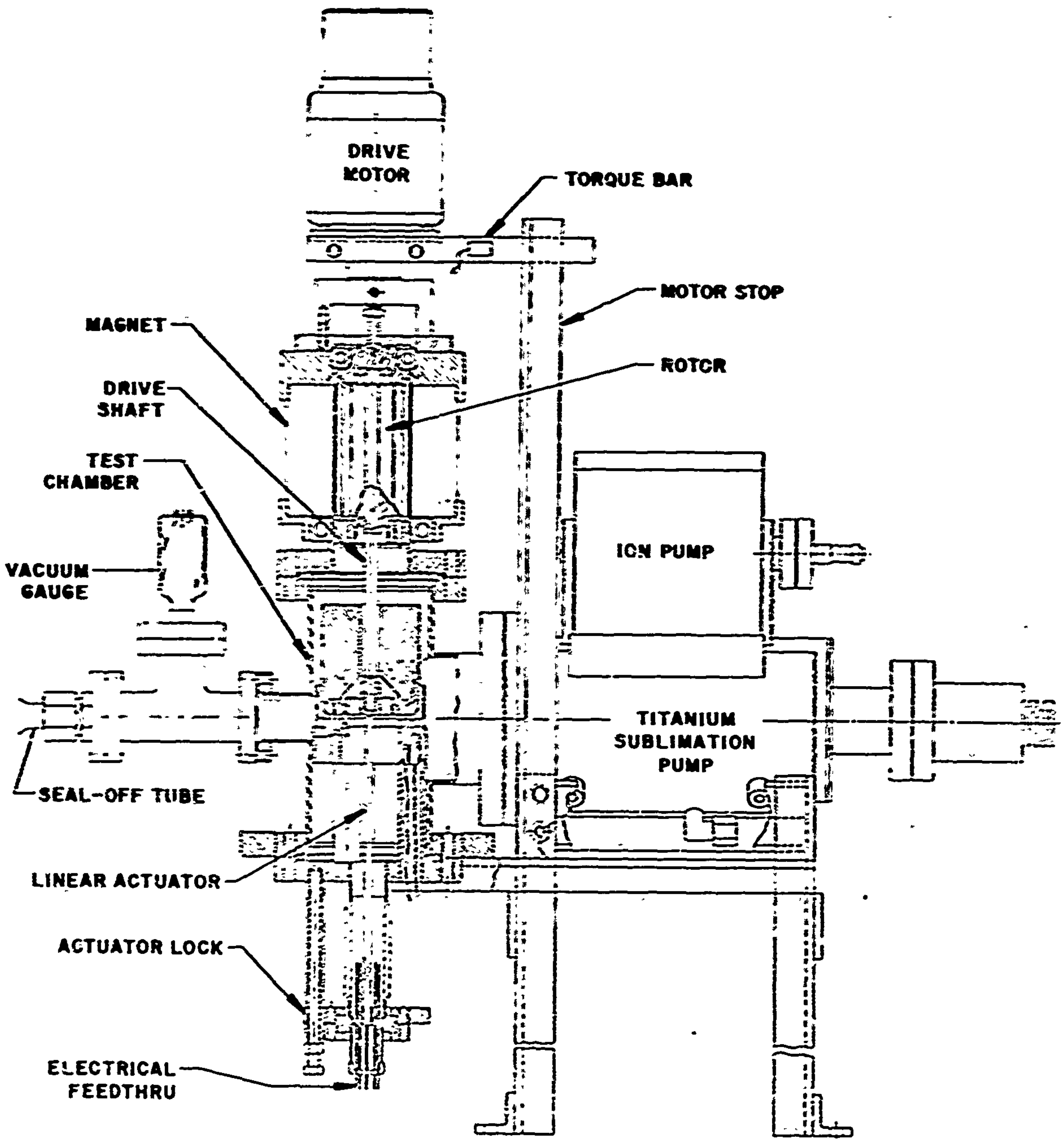


Figure 27. Ultrahigh Vacuum Test Station[82]

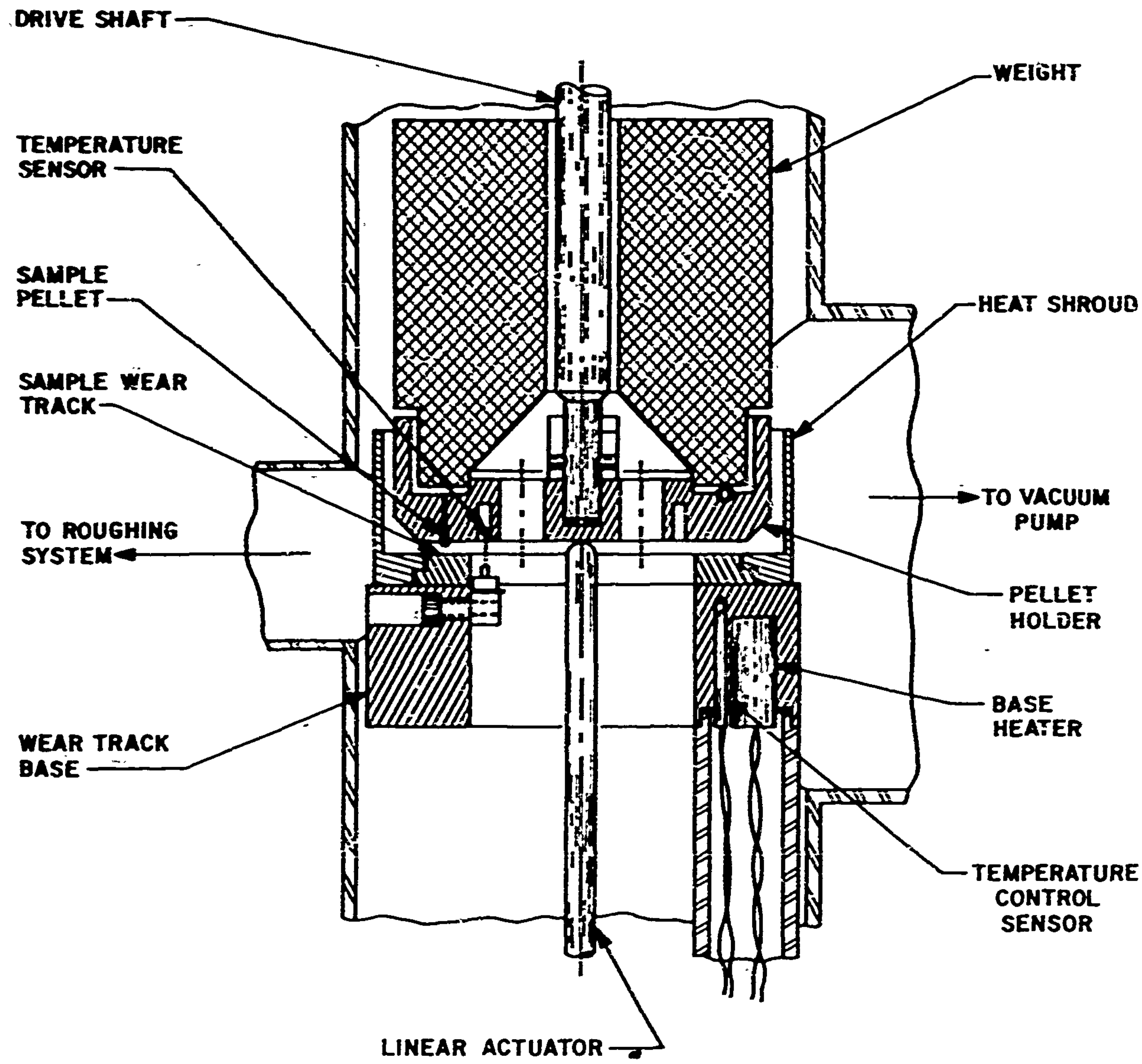
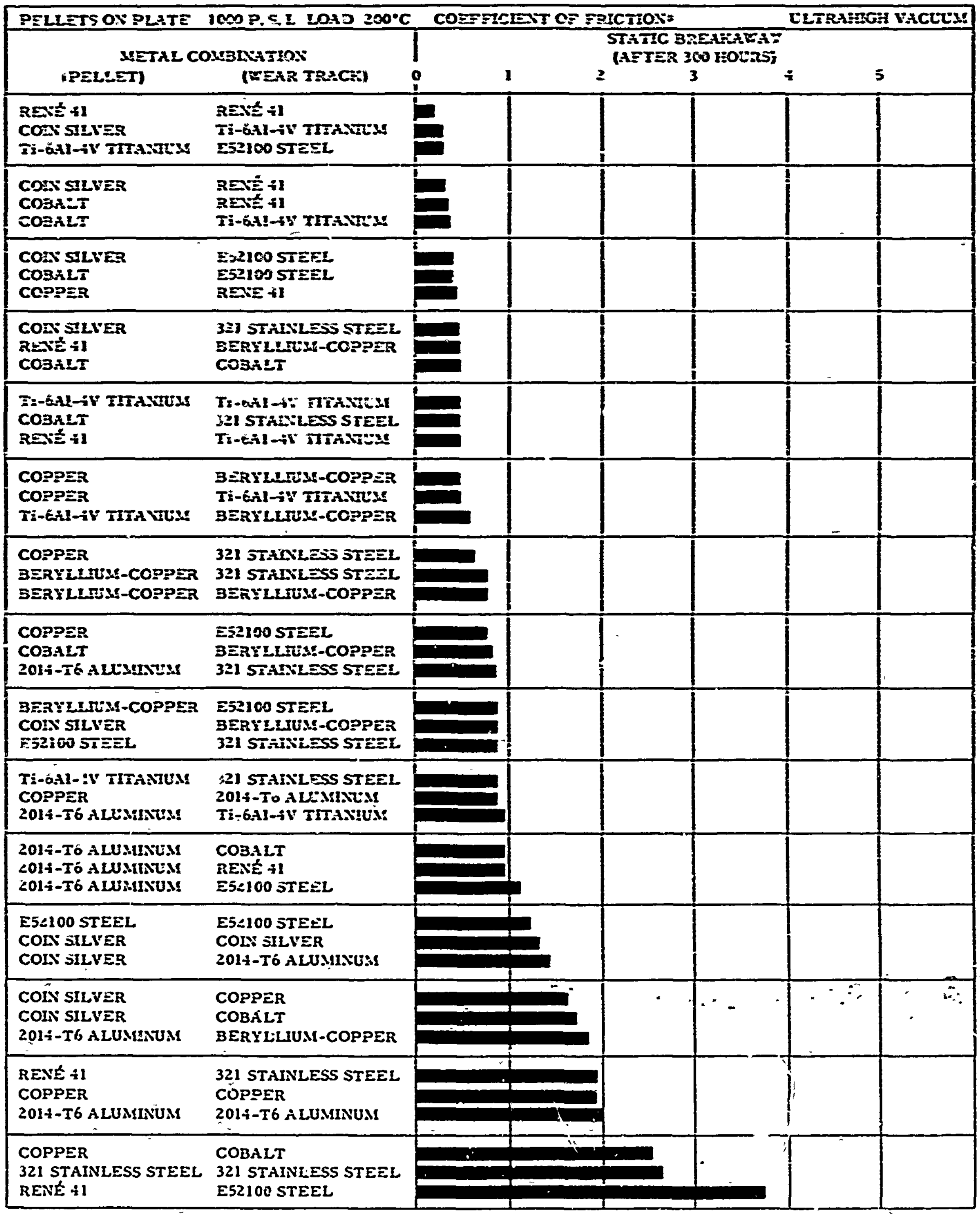


Figure 28. Ultrahigh Vacuum Test Chamber Detail[82]

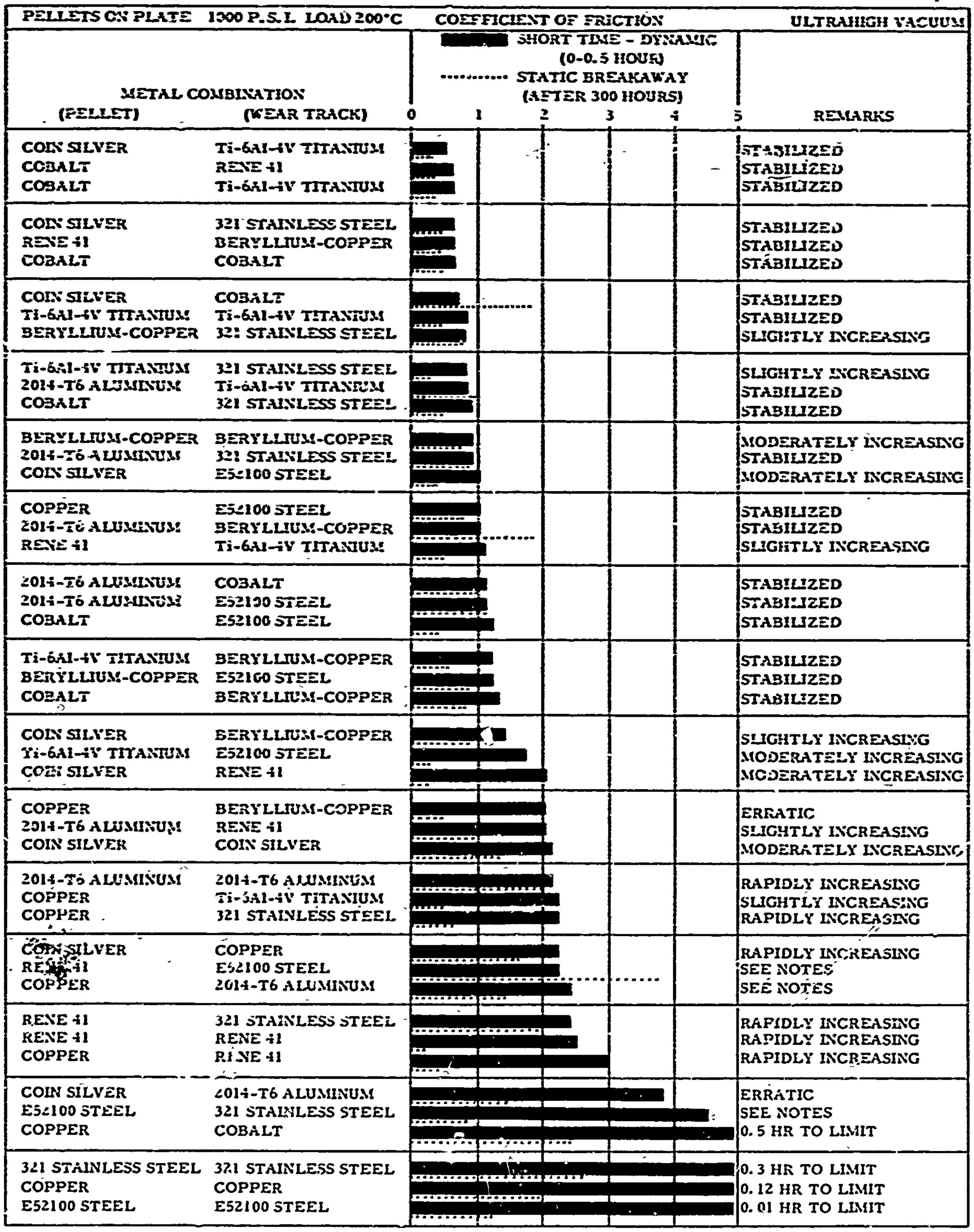
pellets were in stationary contact with the wear track for 300 hours at 200°C. The dynamic coefficient of friction was determined after breakaway at a sliding velocity of 0.4 inch per second. Continuous recordings were made during the following intervals: 0 to 0.5 hour, 0.5 to 5 hours, and 5 to 100 hours.

The coefficient of friction data are summarized in Figures 29, 30, and 31. In Figure 29, the metal couples are ranked in order of increasing static coefficient of friction. In Figure 30, the couples are ranked in order of increasing dynamic coefficient of friction for the short interval (0 to 0.5 hour) test. The complete static and dynamic data are presented in Figure 31. Very little correlation between the



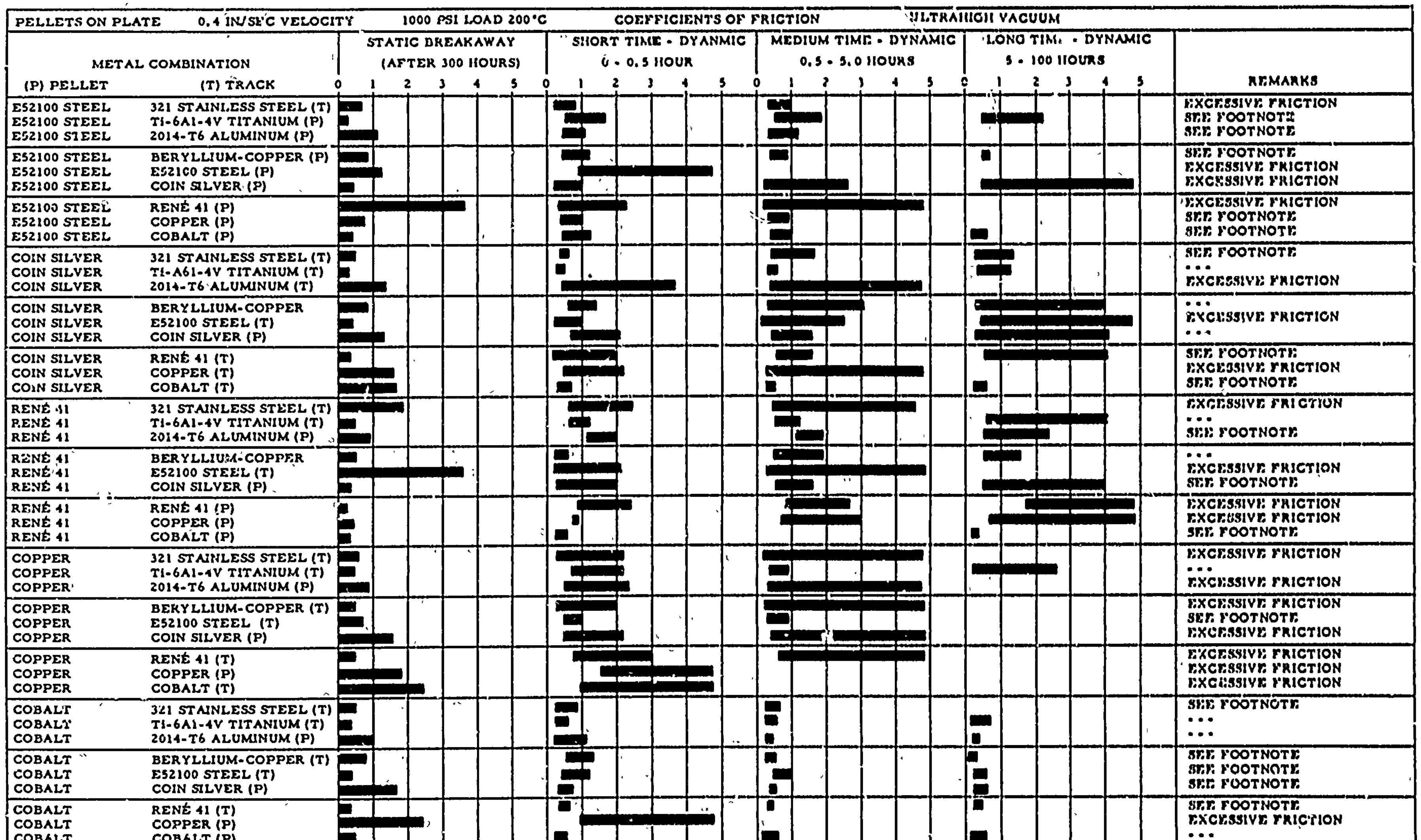
*DATA FROM SINGLE RUN WITH EACH METAL COMBINATION.
NOTE: RANKED ACCORDING TO INCREASING BREAKAWAY COEFFICIENT OF FRICTION.

Figure 29. Static Friction Properties of Structural Metal Couples[82]



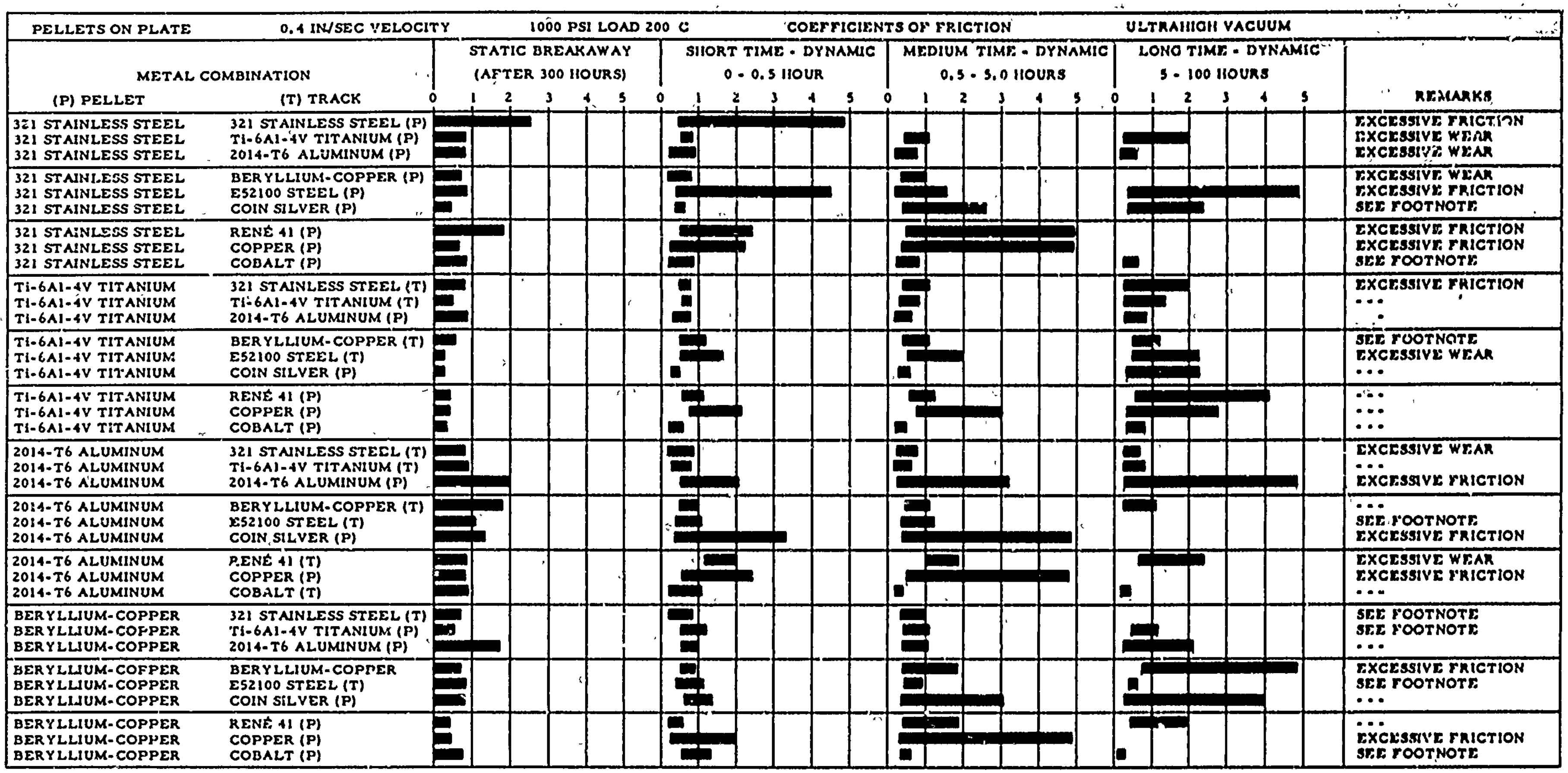
NOTES: MAXIMUM AT 2.4 AT BEGINNING AND NEARLY THE SAME FOR 4.5 HOURS UNTIL A SUDDEN RISE TO 4.9.
MAXIMUM AT 2.2 AT BEGINNING, DROPPED TO 0.2 TO 1.5 WITHIN 1 HOUR, AT 1.4 HOURS APPARENTLY DEBRIS CAUGHT PELLET AND STOPPED ROTATION, RESTARTED AND RAN FOR ANOTHER HALF HOUR AT 0.2 TO 1.5 BEFORE NEXT STOPPAGE.
HIGH FRICTION AT BEGINNING, DROPPED IN 3 HOURS TO 0.2 TO 0.5 AND STABLE FOR NEXT 30 HOURS, MAXIMUM INCREASED TO 4.9 IN NEXT 4 HOURS.
RANKED ACCORDING TO INCREASING COEFFICIENT OF FRICTION.
DATA FROM SINGLE RUN WITH EACH METAL COMBINATION.

Figure 30. Dynamic Friction Properties of Structural Metals[82]



NOTE: TEST ENDED WHEN DRIVING TORQUE AND SOUND DECREASED SIGNIFICANTLY, INDICATING LOSS OF CONTACT BETWEEN TEST SURFACES.
DATA FROM SINGLE RUN WITH EACH METAL COMBINATION.

Figure 31. Static and Dynamic Friction Properties of Structural Metals[82]



NOTE: TEST ENDED WHEN DRIVING TORQUE AND SOUND DECREASED SIGNIFICANTLY, INDICATING LOSS OF CONTACT BETWEEN TEST SURFACES.
DATA FROM SINGLE RUN WITH EACH METAL COMBINATION.

Figure 31. (Concluded)

coefficients of friction and the properties of the materials investigated was noted, except that a low coefficient of friction was observed for cobalt, a metal with a close-packed hexagonal structure. Similar data for metals with a hexagonal structure have been obtained in other investigations. Metal transfer from the pellets to the wear track generally occurred when the pellet material was softer than the wear-track material. No particular trend was observed when the pellets were harder than the wear-track material. Comparative data for four metal couples (2014-T6/321, Co/321, Ti-6Al-4V/321, and 321/321) in air and in ultrahigh vacuum indicated that the static coefficients of friction in air were about one-half of the value obtained under vacuum conditions for all except the 321/321 couple.

Based on the average coefficients of friction, the tendency of the metals investigated to cold weld in ultrahigh vacuum conditions is presented in Table IX.

Table IX. Tendency of Structural Metals to Cold Weld in Ultrahigh Vacuum[82]

Ranked in Order of Increasing Tendency to Bond According to Average Coefficients of Friction			
Static Breakaway* (After 300 Hr. Soak)		Dynamic Coefficient* (Maximum Value)	
Ti-6Al-4V Titanium	0.46	Cobalt	1.43
Beryllium-Copper	0.81	Ti-6Al-4V Titanium	1.59
321 Stainless Steel	0.86	Beryllium-Copper	2.36
René 41	0.86	2014-T6 Aluminum	2.52
Cobalt	0.89	321 Stainless Steel	2.53
Coin Silver	0.92	E52100 Steel	2.86
Copper	1.03	Coin Silver	3.40
E52100 Steel	1.06	René 41	3.63
2014-T6 Aluminum	1.21	Copper	3.80

*Average values from metal combinations of specified metal with itself and the eight other metals.

c. National Research Corporation

Studies on adhesion and related subjects have been conducted at the National Research Corporation since 1960 under the sponsorship of the U.S. Air Force and NASA. In 1960, Atkins, et al[19] summarized the state-of-the-art knowledge of the following:

1) Effect of space radiation on materials.
2) Mechanical properties of materials in a vacuum.
3) Friction in a vacuum.
4) Effect of vacuum on surface electric properties.
5) Meteoroids and their effect on materials.

In 1961, the National Research Corporation began the first of a series of programs sponsored by NASA to determine the conditions under which adhesion of structural metals and alloys would occur in the space environment. Both the positive and negative aspects of adhesion were considered. In reporting these studies,[83] terms defined as follows were used:

1) Adhesion - The solid-state bonding of dissimilar metals.
2) Cohesion - The solid-state bonding of similar metals.
3) Adhesion Coefficient (α) - The ratio of the force required to fracture the bond to the force required to form the bond.
4) Compressibility Ratio (c) - The ratio of the stress applied to form the bond to the actual yield stress of the metals (in the case of dissimilar metals, the yield stress of the softest metal was used).

A cylindrical, notched tensile-type specimen was used to determine the cohesion of selected metal couples at temperatures of 25° to 500°C (Figure 32).[84] These specimens were repeatedly fractured and joined in a vacuum chamber capable of maintaining a pressure of 5×10^{-10} torr; however, because of equipment outgassing, the pressure during testing was in the 10^{-9} torr range. The effects of the following variables on the cohesion properties of OFHC copper, 1018 steel, and 52100 steel were determined: temperature, pressure, time specimens were separated, compressive stress, and time specimens were in contact. The maximum cohesive stress for OFHC copper and 1018 steel are shown in Figures 33 and 34. Cohesion was not observed for the 52100 steel except at temperatures exceeding 400°C.

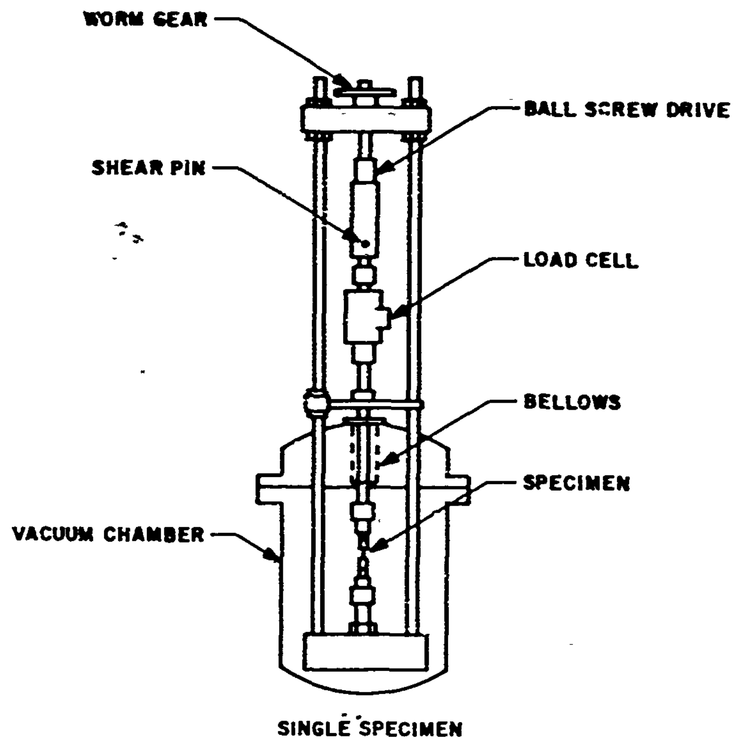


Figure 32. Cohesion Test Apparatus[84]

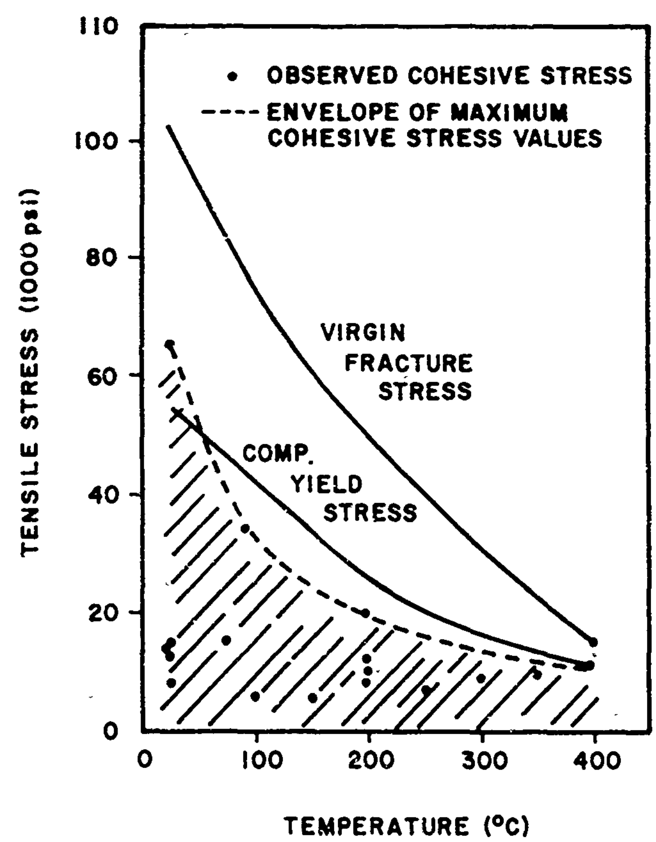


Figure 33. Maximum Observed Cohesive Stress for OFHC Copper Compared to Virgin Fracture Stress and Compressive Yield Stress[84]

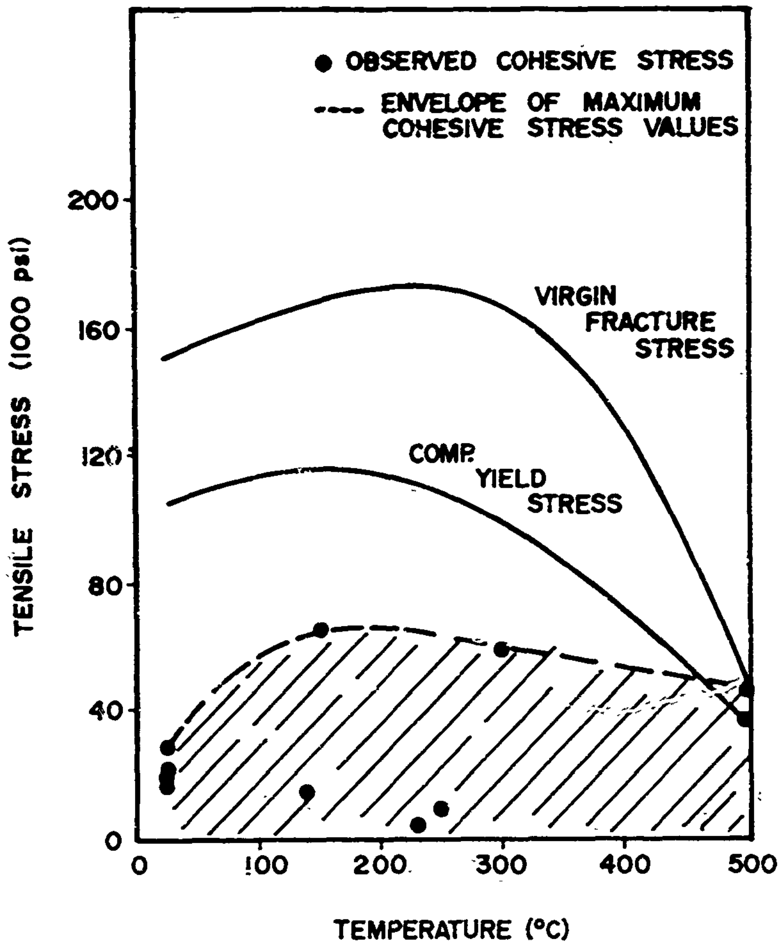


Figure 34. Maximum Observed Cohesive Stress for 1018 Steel Compared to Virgin Fracture Stress and Compressive Yield Stress[84]

Cohesion appeared to be a function of the physical properties of the metals as well as the degree of surface cleanliness. Cohesion was temperature dependent and increased with temperature. The time the specimens were in contact was influential at high temperatures but not at low temperatures. Cohesion of the 52100 hardened steel specimens was not observed at low temperatures, because of the hardness of the steel and its high elastic modulus; however, at temperatures above 400°C, this steel softened and appreciable adhesion occurred. The 1018 and 52100 steels were self-cleaning at 500°C, apparently because the surface oxide was removed by reduction with carbon that diffused to the metal surface.

In follow-on research, the equipment was modified to permit determination of adhesion between dissimilar metals.[85] The fracture-rejoin specimen used in previous work was suitable only for determining the cohesion between similar metals, because the entire specimen was

machined from a single piece of metal. As shown in Figure 35, two wheels in which eight pairs of flat-faced or chisel-edged specimens could be mounted were used, and the wheels were oriented so the specimens were located at right angles to each other. In the previous work with notched, tensile-type specimens, no surface cleaning was needed. In these studies, the contact surfaces were cleaned by wire brushing under vacuum conditions. Test specimens were machined from the following materials in both the hard and soft condition:

1) OFHC copper.
2) AISI 1018 steel.
3) AISI 4140 steel.
4) Type 440 C stainless steel.
5) Titanium.
6) Copper-beryllium (alloy No. 25).

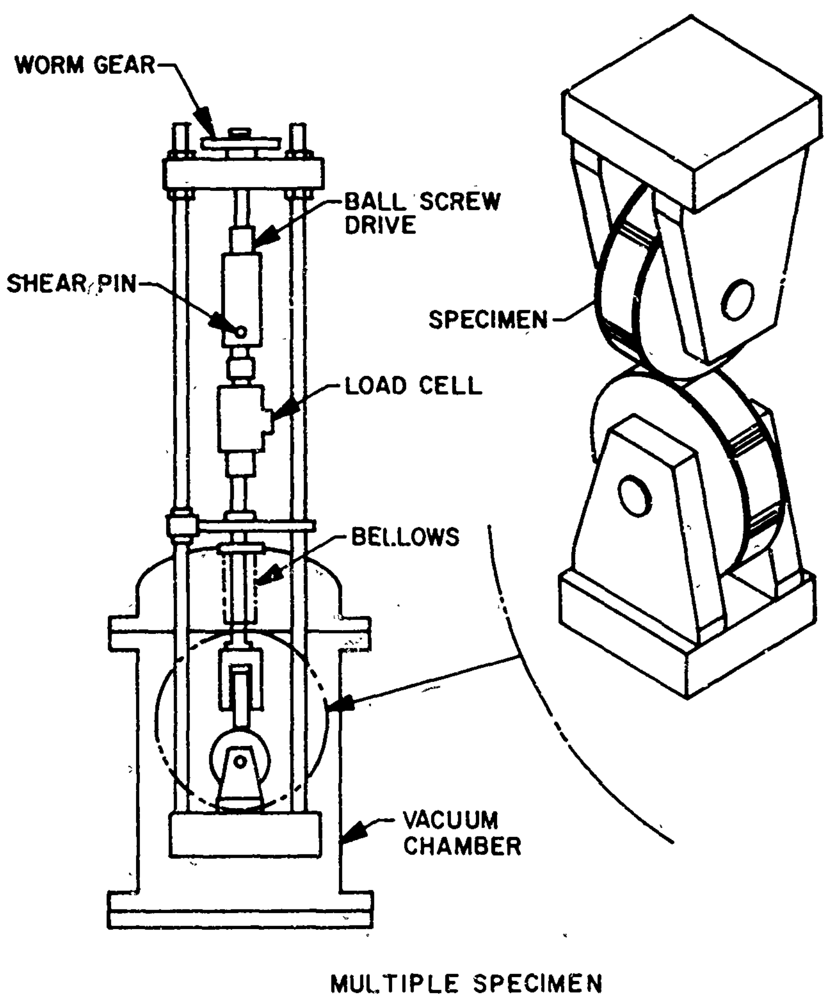


Figure 35. Cohesion Test Apparatus[85]

It was concluded that soft copper had no tendency to adhere to itself or to steel, titanium, or beryllium-copper at room temperature in a vacuum of 10^{-9} torr, even when severely deformed. All specimens were outgassed at 250°C in a vacuum before testing occurred. Wire brushing the specimens in a vacuum resulted in a small degree of cohesion between soft copper specimens at room temperature with slight deformation, but not between specimens machined from soft steel. No adhesion was noted between wire-brushed soft copper and unbrushed steel, titanium, or beryllium-copper at room temperature in a vacuum of 10^{-9} torr with slight deformation. No cohesion between specimens of soft steel and titanium occurred when the specimens were severly deformed in compression at 10^{-9} torr after exposure of the parts at 250°C in a vacuum. In comparing the results of this study with those of the previous programs, it was concluded that much less cohesion between copper couples occurred after the specimens were wire brushed in a vacuum, than when cohesion was determined by the fracture-rejoin technique.

During the last phase of this program, the vacuum equipment was further modified to permit the installation of two ion guns for surface cleaning operations.[86] Each gun consisted of two main sections, a cold cathode ion source,and an electrostatic lens system to focus the ions. The performance of the ion bombardment system was evaluated using both argon and xenon. Using an argon ion source, soft copper specimens were bombarded for 70 hours while a vacuum of 10^{-7} torr was maintained. No cohesion was obtained with the copper couple; however, the lack of cohesion was related to a malfunction in the diffusion pump which resulted in surface contamination of the specimens. Copper specimens were also bombarded with xenon ions for periods of 15 and 30 minutes, and attempts were made to bond the couples. No cohesion occurred, so further studies of the ion bombardment process was deferred. An improved system of wire brushing was used for surface cleaning during the remainder of the experimental program. The following metals were included in this investigation:

1) OFHC copper.
2) AISI 1018 steel.
3) AISI 4140 steel.
4) Type 440 C stainless steel.
5) Copper-beryllium (alloy No. 25).
6) Titanium.
7) Silver.
8) Type 1100 aluminum.
9) Type 2024 aluminum alloy.
10) Type 6061 aluminum alloy.

These metals were in the soft (annealed) or hard (heat treated or cold worked) condition. The data from the adhesion-cohesion tests are shown in Table X.

Based on studies conducted with copper couples, it was concluded that cohesion increased with increasing test temperature. Cohesion was also dependent on the surface cleanliness as reflected by the wire brushing time; i. e., increased cohesion was observed with longer cleaning cycles. Cohesion did not increase proportionally to the applied load when this load exceeded the yield stress. Strong cohesion for most metal couples having a Brinell hardness number less than 150 at 125°C was noted. Similar observations were made regarding the adhesion of dissimilar metals when one of the metals had a hardness less than 150 Brinell hardness number. Adhesion and cohesion between metal couples was appreciable when the test temperature approached 0.3 of the melting point of the metal.

In a recent program conducted for the U.S. Air Force, the National Research Corporation[87] has investigated the adhesion between bare metal surfaces and the effectiveness of selected coatings in preventing adhesion. The materials studied ranged from very soft to very hard materials, and the coatings ranged from soft laminar films to hard oxide surface layers. The adhesion properties of the selected materials were determined at temperatures of 90° to 260°C and stress levels of 0 to 1000 pounds per square inch. The pressure under which adhesion tests were conducted was from atmospheric pressure to 10^{-13} torr or lower.

The adhesion test specimens were fabricated from the following materials:

1) OFHC copper.
2) Type 2014-0 aluminum alloy.
3) 17-7 PH stainless steel.
4) Type 440 C stainless steel.
5) Tungsten carbide.

These materials were tested bare and coated with aluminum oxide, chromium oxide, zirconium oxide, and molybdenum disulfide. The oxide coatings, 0.015 inch thick, were applied to the metal substrates by flame spraying. The 0.0003-inch-thick coating of molybdenum disulfide was applied by the "electrofilm" process.

The test specimens were cylindrical in shape. A specimen set consisted of one rotating cylinder constrained between two fixed cylinders.

Test Pair	Test Load (lbs)	Loading Time (min)	Cleaning Time (min)	Test Vacuum (torr)	Test Temp (°C)	Test Area	Breakaway Load (lb)	Remarks
Cu-Cu s-s	2000	15	None	6.10^{-9}	125		0	
Cu-Cu s-s	2000	15	0.5	7.10^{-9}	125		240	Compares No. 2
Cu-Cu s-s	2000	15	0.5	6.10^{-9}	100		100	
Cu-Cu s-s	2000	15	0.5	6.10^{-9}	100		40	
Cu-Cu s-s	2000	15	5	7.10^{-9}	100		900	Note cleaning time compared to entry above.
Cu-BeCu s-s	2000	15	5	3.10^{-9}	25		25	
Cu-1018 s-s	2000	15	5	3.10^{-9}	25		190	Cu stuck to steel when pulled apart
Cu-Ti s-s	2000	15	5	2.10^{-9}	25		50	
Cu-Cu s-s	2000	15	2	1.2×10^{-9}	25		300	
Cu-Cu s-s	2000	15	3	1.3×10^{-9}	25		220	
Cu-Cu h-h	2000	15	2	1.3×10^{-9}	25		60	Hard copper
Cu-Cu h-h	2000	15	3	5.8×10^{-9}	100		250	Hard copper
Cu-Cu s-s	2000	15	2	3.9×10^{-9}	100		350	
Cu-Cu s-s	2500	15	2	3.1×10^{-9}	100		600	Note increased compression load
Cu-Cu s-s	2000	15	2	5.8×10^{-9}	140		600	
Cu-Cu s-s	2000	15	2	5.0×10^{-9}	140		600	
1018-1018 s-s	2000	15	3	$4.2.10^{-9}$	125	0.060	0	
440C-440C s-s	2000	15	3	$4.0.10^{-9}$	125	0.062	0	
Al-Al s-s	2000	15	3	$3.6.10^{-9}$	125	0.055	320	Stainless steel
CuBe-CuBe s-s	2000	15	3	$3.6.10^{-9}$	125	0.023	0	Stainless steel
CuBe-CuBe h-h	2000	15	3	$3.6.10^{-9}$	125	0.058	0	Stainless steel
Ti-Ti s-s	2000	15	3	$3.6.10^{-9}$	125	0.039	0	Stainless steel
Cu-Ti s-s	2000	15	3	$3.8.10^{-9}$	130	0.062	48	Carbon steel brush
Cu-Al s-s	2000	15	3	4.10^{-9}	130	0.067	800	Carbon steel brush
Cu-CuBe s-s	2000	15	3	4.10^{-9}	130	0.042	400	Carbon steel brush
Ti-Ti h-h	2000	15	3	4.10^{-9}	130	0.023	0	Carbon steel brush
CuBe-CuBe s-s	2000	15	2	4.10^{-9}	130	0.023	0	Carbon steel brush
Cu-Cu h-s	2000	15	2	5.10^{-9}	125	0.065	340	Carbon steel brush
Cu-1018 s-h	2000	15	2	5.10^{-9}	125	0.046	300	Carbon steel brush
Cu-4140 s-h	2000	15	2	5.10^{-9}	125	0.028	40	Carbon steel brush
Cu-440C s-h	2000	15	2	$4.5.10^{-9}$	125	0.024	40	Carbon steel brush
Cu-CuBe s-h	2000	15	2	$4.5.10^{-9}$	125	0.028	40	Carbon steel brush
Cu-Ti s-h	2000	15	2	$4.5.10^{-9}$	125	0.042	160	Carbon steel brush
Al-Cu s-h	2000	15	2	$4.5.10^{-9}$	125	0.044	300	Carbon steel brush
CuBe-CuBe s-h	2000	15	2	$4.5.10^{-9}$	125	0.025	0	Carbon steel brush
2024-2024 h-h	1000	15	2	$3.1.10^{-9}$	125	0.062	0	Differences in pressure in loading
6061-6061 h-h	1000	15	2	$3.0.10^{-9}$	125	0.065	40	Differences in pressure in loading
6061-2024 h-h	2000	15	2	3.10^{-9}	125	0.062	80	
2024-1018 h-s	2000	15	2	$3.5.10^{-9}$	125	0.050	0	
6061-Cu h-s	2000	15	2	$3.2.10^{-9}$	125	0.062	120	
6061-1018 s-s	2000	15	2	3.10^{-9}	125	0.062	40	
6061-Ag s-s	2000	15	2	$3.5.10^{-9}$	125	0.062	25	
6061-CuBe s-s	2000	15	2	3.10^{-9}	125	0.029	0	
2024-2024 h-h	1000	15	2	$3.2.10^{-9}$	125	0.062	0	Differences in pressure in loading
6061-6061 h-h	1000	15	2	$2.8.10^{-9}$	125	0.062	300	Differences in pressure in loading
2024-2024 h-h	2000	15	2	3.10^{-9}	125	0.062	0	
Au-Au s-s	2000	15	0	$1.5.10^{-9}$	125	0.073	0	No brush cleaning
Au-Au s-s	2000	15	0.5	$1.5.10^{-9}$	125	0.034	340	
Au-Cu s-s	2000	15	2	$1.8.10^{-9}$	125	0.073	420	
Au-1018 s-s	2000	15	2	$2.5.10^{-9}$	125	0.065	170	
Au-Al s-s	2000	15	2	$2.5.10^{-9}$	125	0.090	800	
2024-2024 h-h	2000	15	2	$3.5.10^{-9}$	125	0.0625	72	
6061-6061 h-h	2000	15	2	3.10^{-9}	125	0.068	60	
2024-2024 s-s	2000	15	2	3.10^{-9}	125	0.063	180	2024 annealed - 775 - 1/2 hour.

Table X. Results of Adhesion-Cohesion Tests[86]

The rotating cylinder could be moved through an arc of 180 degrees, either loaded or unloaded. Fifteen sets of specimens were stacked on a shaft for each series of experiments.

The vacuum chamber (Figure 36) used during the experimental studies could maintain a pressure of 10^{-13} torr or less. The arrangement of the adhesion apparatus is shown in Figure 37.

Before testing, the bare specimen faces were ground, polished, and liquid honed using 325 mesh aluminum oxide powder. The oxide-coated specimens were finished with 2/0 polishing paper. Specimens coated with molybdenum disulfide received no further treatment before testing.

Static and dynamic adhesion tests were conducted at temperatures of 90°, 150°, and 260°C using interface stresses of 100 and 1000 pounds per square inch. The adhesion properties of the bare metals were determined in argon (760 torr) and in a vacuum of 7×10^{-12} torr. The adhesion properties of both coated and uncoated metals were determined in a vacuum of 5×10^{-12} torr or less. The test data are summarized in Figures 38 and 39.

Based on the results of this program and a review of the literature on adhesion, the following interrelated parameters were deemed particularly important in controlling adhesion:

1) Surface cleanliness.
2) Plastic stress-strain at the contacting interface.
3) Mechanical properties (elastic modulus, yield stress, hardness, and ductility).
4) Test temperature.
5) Lattice structure.
6) Surface contour.
7) Relative surface motion.
8) Vacuum environment.

A number of recommendations to decrease or prevent adhesion were advanced as follows:

1) Use high-modulus hard materials with limited ductility.
2) Maintain nonmetallic film such as molybdenum disulfide between contacting surfaces.
3) Avoid abrasive motions that might remove oxide layers or films of adsorbed gases.
4) Avoid contact stress near the yield stress of the softer metals.

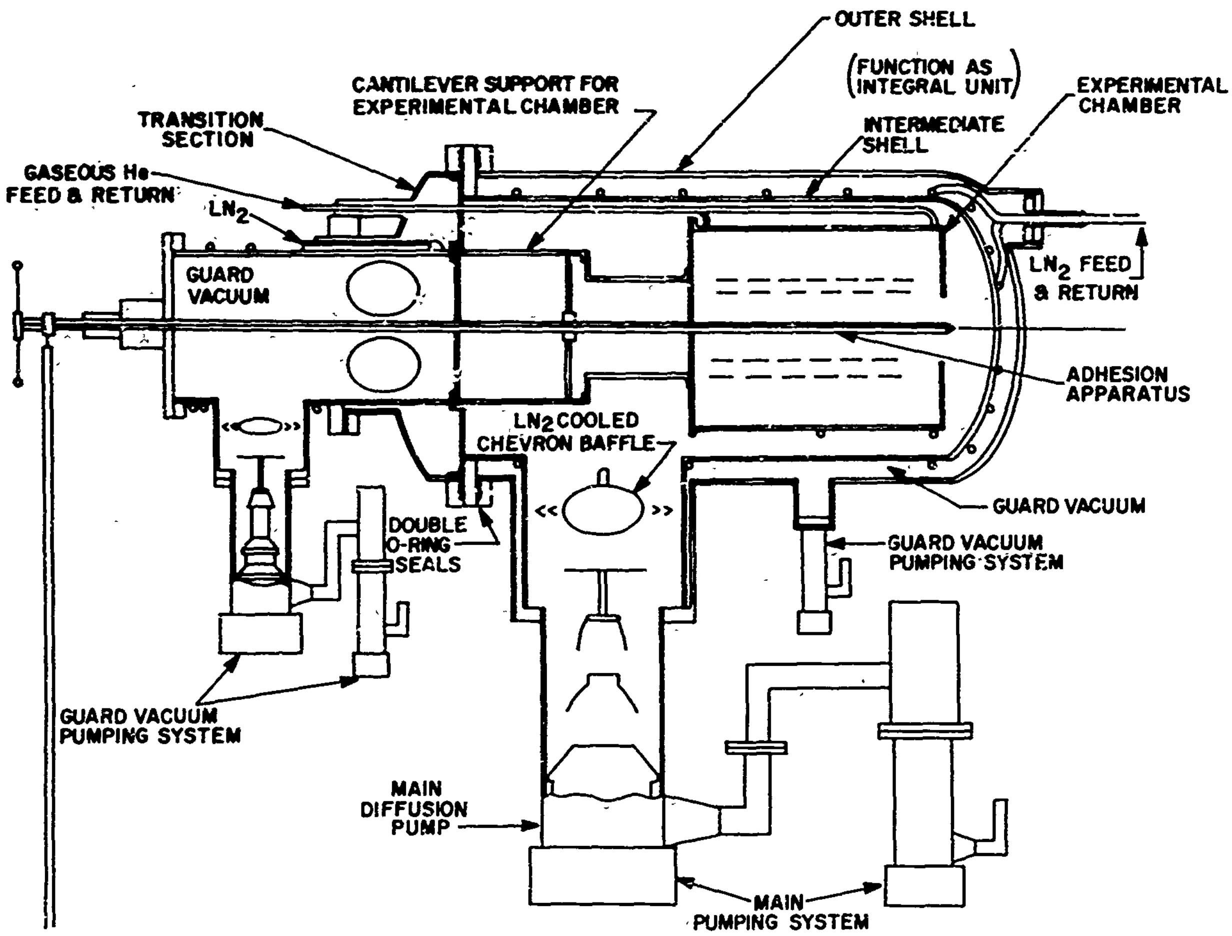


Figure 36. Extreme High Vacuum Chamber[87]

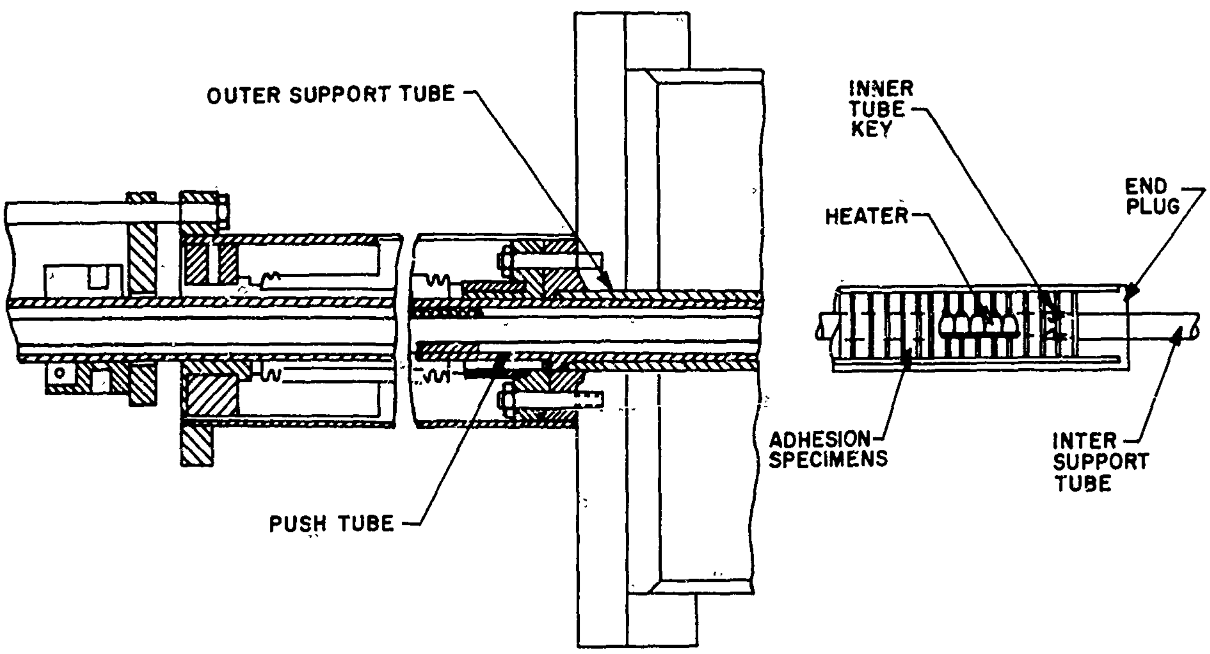


Figure 37. Adhesion Test Equipment[87]

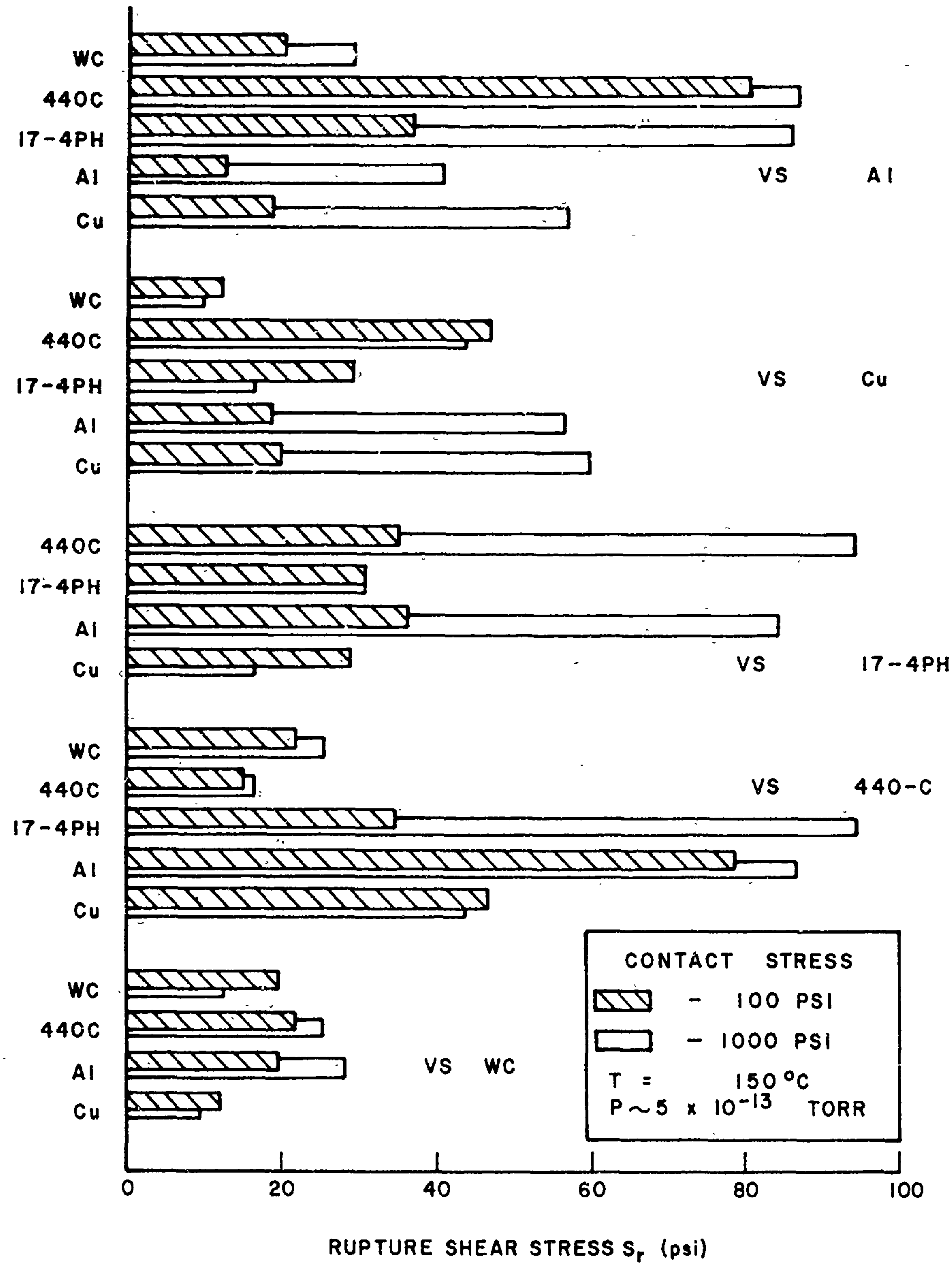


Figure 38. Rotational Stress to Shear Residual Cold Welding After Release of Contact Stress for Various Material Combinations in Vacuum[87]

5) Avoid operating temperatures that exceed one-half of the absolute melting temperature.
6) If possible, avoid high vacuum environment.
7) Use tenacious oxide or other inorganic coatings to prevent metal-to-metal contact.
8) Minimize the contact time under load, especially at high temperatures.

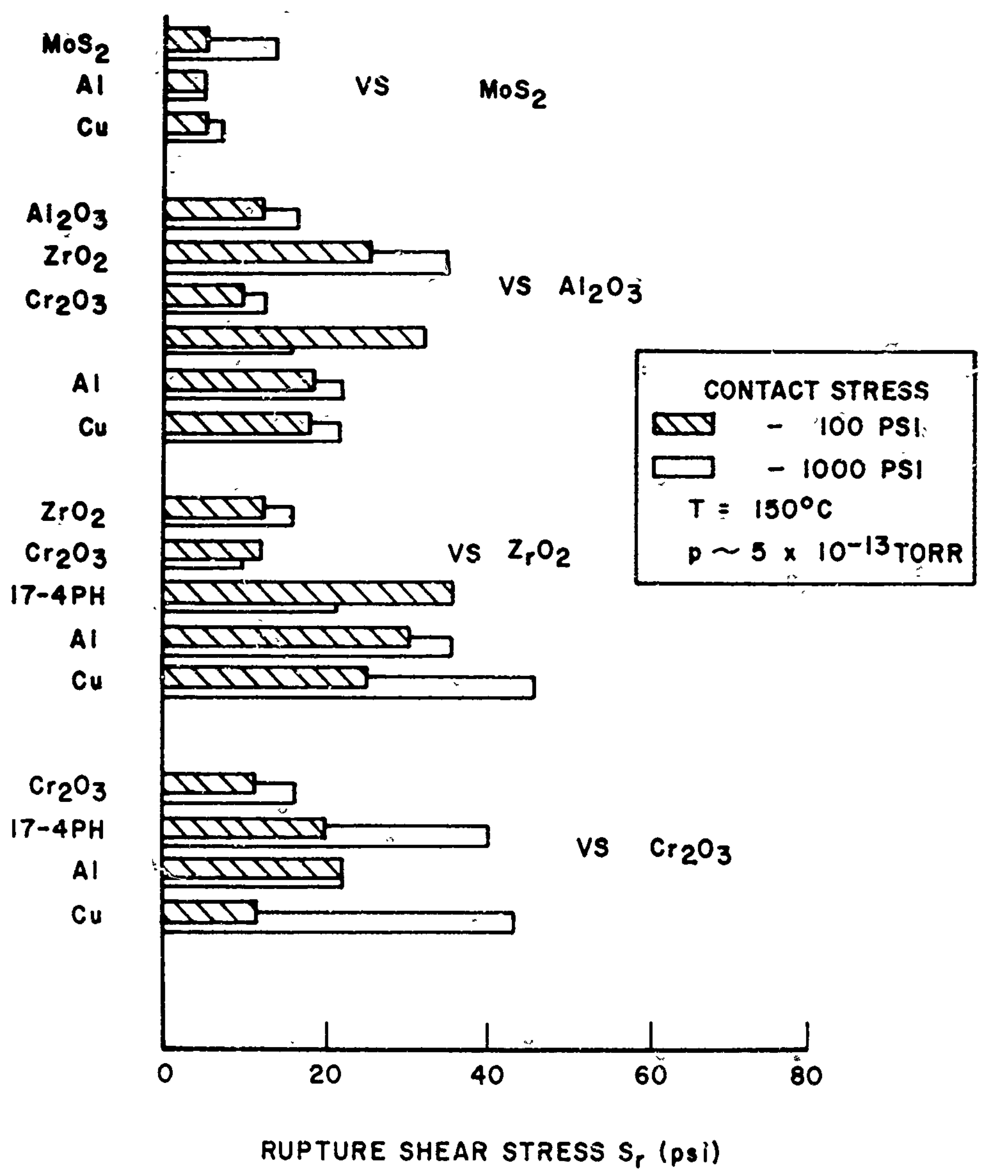


Figure 39. Rotational Stress to Shear Residual Cold Welding After Release of Load for Coated Materials[87]

In a recent study, the effect of lattice solubility on the tendency for adhesion to occur was investigated.[83] Dissimilar metal couples using metals that were completely miscible at room temperature (copper-gold, copper-nickel, silver-gold, and columbium-tin) and metals with less than 0.1-percent solubility at room temperature (copper-tin, silver-beryllium, silver-nickel, and gold-lead) were tested. As in previous work, the principal variables controlling adhesion were surface cleanliness, temperature, and loading. The adhesion data are summarized in Figure 40. Adhesion was obtained for both solubility

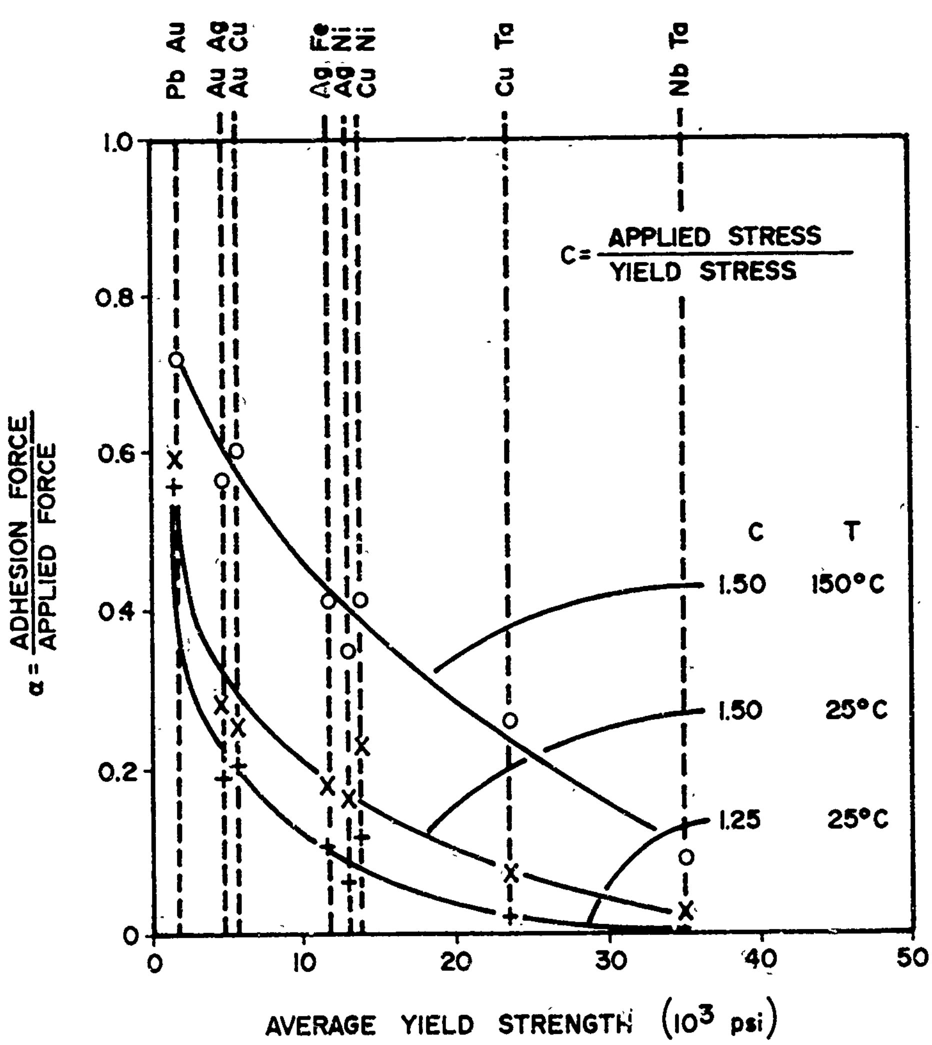


Figure 40. Adhesion Coefficient as a Function in Yield Stress for Various Sample Materials[83]

conditions. As in previous work, the variables controlling adhesion were degree of cleanliness, temperature, and load. It can also be seen that adhesion was inversely related to the hardness of the metals.

d. Atomics International

Investigations of friction phenomena were conducted in conjunction with the development of the Systems for Nuclear Auxiliary Power (SNAP) inflight reactor by Atomics International.[58] Bearing compatibility had to be established for materials that would be subjected to temperatures ranging from ground temperature to 1300°F and pressures ranging from atmospheric to below 10^{-9} torr. Sixty-seven material pairs comprising metals, ceramics, graphite, and lubricated specimens were evaluated in a vacuum of 10^{-9} torr at temperatures up to 1000°F. It was found that preformed contaminant films applied to the metal surfaces reduced the coefficient of friction significantly. Among the most satisfactory of the films investigated was sodium-silicate bonded molybdenum disulfide and molybdenum diselenide.

e. Litton Industries

An early investigation of surface friction and wear was conducted by the Litton Industries in 1958.[59] The friction characteristics of the following metals were determined in air and in a vacuum of 10^{-6} torr:

1) Commercially pure aluminum and Type 2024-T4 aluminum alloy.
2) Brass.
3) Copper.
4) Type 304 stainless steel.
5) Beryllium copper.
6) 52100 steel.
7) Various electroplatings.

The tests were conducted by measuring the tangential force developed between the sliding blocks. Although fundamental relationships were not developed during these early studies, several trends were noted. When dissimilar metal couples were tested, the softer material transferred to the harder material. Under good vacuum conditions, the wear products consisted of particles torn from the contacting surfaces, and because of work-hardening, these particles were harder than the base materials. There were indications that friction was 60 percent higher in vacuum than in air, and that in both cases, running friction increased by about 50 percent within 10 minutes in either air or in vacuum, then friction tended to level off.

f. North American Aviation, Incorporated, Rocketdyne

In 1962, Rocketdyne[90] conducted research to accumulate friction data for comparison with those obtained by Litton Industries. Six material combinations were selected for this work: aluminum, stainless steel, and silver, chromium, cadmium, and nickel electroplated on AISI 1090 steel. During the first phase of testing, a series of one-minute tests under two load conditions was conducted in air and in a vacuum. Then, running tests were conducted for 30 minutes in air and in a vacuum. The results indicated there was no consistent trend for the initial friction to be higher in a vacuum than in air. Although the results obtained during running tests varied, friction under vacuum conditions was slightly higher after 30 minutes running time than was atmospheric friction.

g. Lockheed Missiles and Space Company

Extensive research on the behavior of materials in the space environment has been conducted by the Lockheed Missiles and Space Company since the early 1960's. In 1961, Clauss[91] discussed the friction and wear of gears, bearings, and electrical contacts under high vacuum conditions. Experiments to evaluate the performance of various lubricants in a vacuum of 10^{-6} torr or less was discussed, and preliminary plans to study the behavior of sliding electrical contacts were outlined. In later research sponsored by the Air Force, the operating characteristics of electrical slip-rings and brushes were determined in a vacuum of 10^{-7} to 10^{-8} torr.[12,92] The sliding friction, as measured by the noise contributed to the electrical circuit, could be reduced several orders of magnitude with lubricants. The use of molybdenum disulfide-impregnated silver contacts was investigated. Clauss, et al, also discussed the possible use of soft metal films, such as gold and silver films, as lubricants for sliding electrical contacts.[12] Such films have been used successfully for lubricating the bearings of rotating-anode X-ray tubes and are subject to relatively high temperatures up to 1100°F in a vacuum of 10^{-6} to 10^{-8} torr. During the development of equipment to simulate secondary radiation for a large environmental chamber, slip rings and brushes were selected as the most suitable means to supply power to the radiation simulation source.[26] Studies were conducted to evaluate brush materials riding on slip rings plated with silver or gold. The compositions of the bru' ı materials are shown in Table XI. A slip ring assembly to study the performance of several brush materials simultaneously was constructed. The tests were conducted at room temperature in a vacuum of 10^{-6} torr. Various current densities were used and the brush behavior was determined by noise measurements. The brush wear was also measured. These

studies indicated that brushes with the following composition performed most satisfactorily from the standpoints of minimum wear and minimum noise: 82.5 to 85Ag-2.5Cu-12.5 to 15 MoS_2. These results were verified by additional tests in a vacuum of 10^{-9} torr.

Table XI. Compositions of Brush Materials[92]

Brush	Composition (% wt)			
	Ag	Cu	MoS_2	Graphite
1	97.5	0	2.5	
2	95	0	5	
3	90	0	10	
4	85	0	15	
5	92.5	5	2.5	
6	87.5	10	2.5	
7	85	10	5	
8	85	5	10	
9	82.5	15	2.5	
10	80	15	5	
11	80	10	10	
12	80	5	15	
13	75	15	10	
14	75	10	15	
15	70	15	15	
16	90			10
17	90			10
18	80			20
19	80			20

During the course of these investigations, a number of literature searches were conducted. Annotated bibliographies were prepared on cold welding in a vacuum,[93] metal-to-metal adhesion,[94] and radiation effects on spacecraft materials.[95]

h. Battelle-Columbus

Research on the solid-state bonding of aluminum was conducted in a chamber whose pressure could be maintained at 10^{-6} torr at temperatures up to 1000°F.[96] The most effective method used to remove surface contaminants consisted of chemical cleaning outside the chamber followed by wire brushing in a vacuum prior to welding. The welding temperature had a pronounced effect on the ability to form

strong bonds. Bonds could be made at 900°F with minimum deformation, ~5 percent, and significantly higher deformations, ~30 percent, were required for bonding at 500°F. The use of an intermediate foil of copper or copper-silver eutectic alloy between the faying surfaces increased the ease of bonding.

i. Soviet Research

Research on friction under ultrahigh vacuum conditions has been conducted in the Soviet Union. In 1963, Golego[97] reported on studies made in a vacuum of 10^{-9} to 10^{-10} torr with 30 metals representing all groups in the periodic system: aluminum, magnesium, silicon, scandium, titanium, vanadium, chromium, iron, cobalt, nickel, copper, zinc, yttrium, zirconium, niobium, molybdenum, silver, cadmium, indium, tin, antimony, lanthanum, praseodymium, neodymium, dysprosium, erbium, platinum, thallium, lead, and bismuth. The friction experiments were conducted at room temperature with a load equal to 0.05 times the yield strength of the metal applied normal to the specimen interface; the contacting surfaces moved at a speed of one meter per second relative to each other. During the first series of tests, the coefficient of friction was measured for similar metal couples comprised of the metals listed above. The coefficient of friction varied from 0.8 to 6.5, depending on the mechanical strength of the metal, the load applied, and the rate at which adhesion occurred. The effect of the mutual solubility of metals on the coefficient of friction was investigated. Iron-chromium, iron-aluminum, and iron-titanium couples had coefficients of friction of about 1.4 to 2.7. The room temperature solubility of chromium, aluminum, and titanium in iron is 100, 32, and 3 percent, respectively. Iron-antimony (antimony solubility, seven percent), iron-zirconium (zirconium solubility, 0.15 percent), and the mutually insoluble iron-silver, iron-scandium, iron-magnesium, and molybdenum-copper couples had low coefficients of friction, about 0.2 to 0.6. Some slight indication of adhesion was observed with the iron-silver and molybdenum-copper couples. The effect of crystal lattice structure and atomic diameter on friction and adhesion was investigated. Dissimilar metals having similar crystal lattices and slightly different atomic diameters of 1 to 13 percent (iron-copper, iron-chromium, iron-aluminum, bismuth-antimony, yttrium-dysprosium, and praseodymium-neodymium) showed evidence of adhesion. The coefficients of friction for these metals were 0.5 to 3.3. Metals with similar crystal lattices and very different atomic diameters (cobalt-yttrium and iron-lead) showed no tendency to bond. Dissimilar metals having different crystal lattices and slightly different atomic diameters of 1.5 to 15 percent (iron-titanium, iron-zinc, and iron-cobalt) exhibited a tendency to bond and the coefficients of friction

were high. Metals having different crystal lattices and very different atomic diameters of 18 to 43 percent (iron-yttrium, iron-scandium, cobalt-yttrium, iron-magnesium, iron-antimony, and iron-bismuth) showed no evidence of adhesion and their coefficients of friction were low. On the basis of these studies, Golego concluded that differences in crystal lattice structure have little effect on the tendency for metals to bond; however, the difference in atomic diameter influences adhesion. If the atomic diameter of two metals do not exceed 15 to 18 percent, adhesion will occur. Adhesion will not occur if the atomic diameters differ by more than about 18 percent.

In 1966, Balakin and Khrenov[98] discussed the effect of vacuum on the cold welding process. In analyzing this process, it was concluded that high deformations are required for cold welding because of the film of adsorbed gases on the metal surfaces. Calculations of the time required to form a monolayer of gas (air) on a metal surface were presented. A linear relationship between pressure and the time required to form a monolayer of gas was indicated.

Verkin, Kravchenko, and Lyulichev[99] discussed research on the formation of copper and aluminum bonds in various degrees of vacuum. In particular, the effect of surface cleanliness (as reflected by the vacuum conditions) on the deformation required for bonding was investigated. In a vacuum of 10^{-5} torr, the deformation required for bonding copper was 38 percent. The deformation decreased to about seven percent when copper was bonded in a vacuum of 10^{-9} torr. A similar relationship was observed when aluminum was bonded.

j. Additional Research on Adhesion, Friction, and Lubrication

A number of additional programs on various aspects of adhesion and friction phenomena have been conducted by other organizations, and several will be mentioned briefly. In 1962, Horton[100] reported on an investigation of the characteristics of hot-pressed molybdenum disulfide/metallic powder brushes for use in motors exposed to the space environment. The orientation of the plane of laminations with respect to the brush axis was found to be important from the standpoint of brush wear. Wolkowitz and Ranish[101] investigated the friction and wear characteristics of several metal-to-metal and metal-to-nonmetal couples in 1964. The construction of equipment to study adhesion and friction in a vacuum was reported by Wieser[102] and Liu, Layton, and Tarpin.[103] In an early investigation in 1960, Liu[104] studied the sliding friction of copper under a wide range of conditions. In 1960, Ling[105] reviewed the following areas of research conducted under the sponsorship of the Air Force:

1) Theoretical study of sliding friction between unlubricated surfaces.
2) Asperity distributions on metallic surfaces.
3) A model study of metallic surface asperities.
4) Bond interface temperature distributions.
5) Experimental and theoretical studies of adhesion in a partial vacuum at elevated temperatures.

The research on dry lubricants for use in spacecraft applications is impressive, and the voluminous literature on friction and lubrication should be consulted for detailed discussions of this work (a few references are cited below). The mechanism of lubrication for solid carbon materials has been studied at pressures ranging from atmospheric to 10^{-9} torr by Buckley and Johnson.[106] In 1965, Flom, Haltner, and Gaulin[107] discussed the results of measurements of sliding friction on copper surfaces for the following five lamellar solids: molybdenum disulfide, tungsten sulfide, cadmium iodide, bismuth iodide, and phthalocyanine. The friction studies were conducted in a vacuum of 10^{-6} torr. There was no evidence that the sliding behavior of any of these materials was improved by the presence of gas or vapors. Each material evolved considerable quantities of gas during sliding. The role of vapor lubrication mechanisms in molybdenum disulfide was also studied by Haltner[108] in a vacuum as low as 10^{-9} torr. Sliding friction and the performance of bearings in a vacuum was investigated by Brown, Burton, and Ku.[109] Lubricated and unlubricated slides and bearing assemblies enclosed in individually ion-pumped chambers were tested at room temperature in a vacuum of 10^{-7} to 10^{-9} torr up to 270 days. Several molybdenum disulfide compounds provided adequate lubrication for 60 to 270 days. Limited friction studies were also conducted at temperatures between -320° and 300°F. The fundamental properties of molybdenum disulfide were further investigated by Ku and Tyler[110] in 1965. Evaluation of dry film lubricants for spacecraft applications was also undertaken by Evans, Vest, and Ward[111] of the NASA Goddard Space Flight Center. For rolling applications, such as occur in a ball bearing, a fully machined ball retainer of 60-percent Teflon and 40-percent glass fiber plus molybdenum disulfide proved to be most effective. Dry lubricants for bearing applications have also been investigated by Bowen.[112]

The reports on some investigations of adhesion were not available for this report. For example, research on cold welding in a vacuum is in progress at the Franklin Institute[113] under a contract from the Office of Naval Research. Metal-to-metal adhesion studies have been conducted with copper. Additional work with other metals is underway also.

Section V. ADHESION AND FRICTION IN THE SPACE ENVIRONMENT

Adhesion and friction experiments in the space environment have been planned and conducted. While most of the knowledge concerning these phenomena has been acquired under simulated conditions of ultrahigh vacuum, a well-planned experiment conducted in outer space can produce much useful data. If the apogee and perigee of the orbiting spacecraft are sufficiently high, the experiments can be conducted under vacuum conditions that are currently beyond the state-of-the-art. In addition, the studies can be conducted in an environment that is difficult to simulate on the earth; i. e., under conditions that combine ultrahigh vacuum, solar radiation, earth reflection, etc. Although some information on friction and wear can be obtained from the successful operation or failure of various spacecraft, such an approach is somewhat slow and unreliable; in addition, the data are not quantitative, since the coefficient of friction is not measured. A sounder approach is to design an experiment specifically for gathering data on adhesion or friction. In the following sections, the data acquired during the Ranger space flights are discussed, and plans for other experiments in space are reviewed.

1. Ranger Friction Experiments

In 1961, the coefficients of friction for several lubricated and unlubricated metallic and nonmetallic couples were measured in the space environment during the flights of Ranger 1 and Ranger 2.[114] The friction experiment was designed to obtain data at altitudes corresponding to vacuums of 10^{-12} to 10^{-16} torr; however, because of spacecraft malfunctions, these altitudes were not attained. Nevertheless, valuable friction data were acquired and analyzed.

The friction experiment assembly is shown in Figures 41 and 42. Twenty disk specimens were spaced along a drive shaft, and two 0. 125-inch-diameter hemispherical riders were positioned on each side of the disks. An 0. 3-pound load was applied normal to the surface of the disk. The drive shaft rotated at 28 revolutions per minute. Strain gages were used to measure the frictional force during testing. Detent mechanisms were attached to each rider assembly, so these assemblies could be lifted from the disks in case seizure occurred or friction became excessive. Appropriate telemetry was incorporated in the friction experiment design to facilitate data acquisition. A switch closure in the spacecraft command controller and sequence activated the assembly 367 minutes after launch.

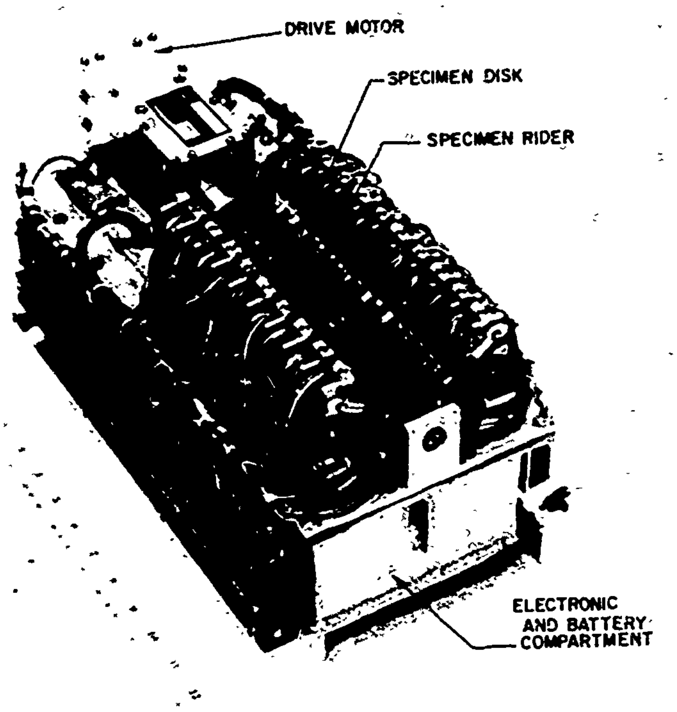


Figure 41. Friction Experiment Assembly with Temperature Control Surfaces Removed[114]
(Courtesy, Jet Propulsion Laboratory)

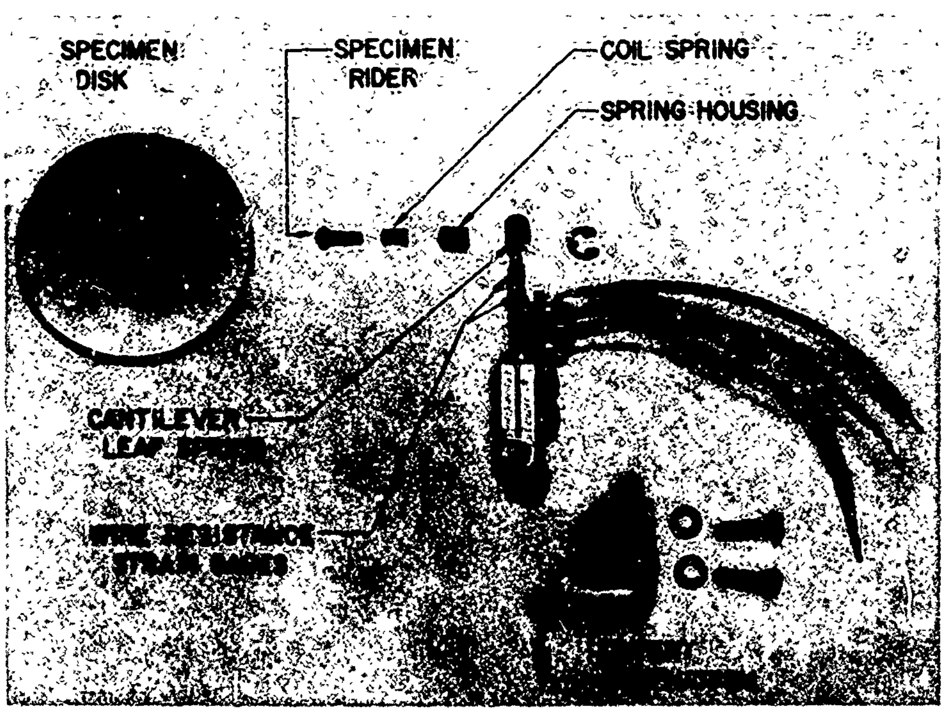


Figure 42. Rider and Disk Assembly Details[114]
(Courtesy, Jet Propulsion Laboratory)

A complete list of the materials evaluated during the friction experiment is shown in Table XII. Included in this list are typical structural alloys used in spacecraft hardware, electrical contact materials, and a number of lubricants. The friction experiment assemblies were leak tested in a vacuum of 10^{-6} torr before being installed in the spacecraft; also, friction data were acquired for comparison with the data obtained in the space environment.

Ranger 1 was launched on 23 August 1961 but did not reach its programmed orbit because of a malfunction in the second stage of the launch vehicle. The spacecraft was placed in a low-altitude orbit having an apogee of 504 kilometers and a perigee of 170 kilometers, instead of an ellipitcal orbit with a very high apogee. Because of the nonstandard orbit, spacecraft telemetry on the friction experiment was not received until the next day (13 hours and 20 minutes after launch). The period during which friction data were received is shown in Table XIII along with the altitude of the spacecraft and the associated vacuum conditions. Data transmission ended when the experiment was turned off at a predetermined low-battery voltage level.

The coefficient of friction data was plotted versus time for each disk and rider combination. Although there were several sources of error inherent to this experiment, it is estimated that the standard deviation for the coefficient of friction data near 0.2 was ±0.035 and ±0.05 for data near 1.0.

The coefficient of friction data for unlubricated metal and ceramic materials is shown in Figure 43. Included are data obtained in air, under laboratory vacuum conditions, and during the flight of Ranger 1. Similar data for lubricated couples are shown in Figure 44. An accurate comparison of the data obtained under laboratory vacuum conditions and space conditions was not possible, because of the difference in running times and the same friction experiment assembly was not used for both tests. However, there did not appear to be any systematic variation in the data. The complete coefficient of friction data are summarized in Table XIV.

Table XII. Composition of Materials Tested During Space Friction Experiment[114]

Material	Commercial Designation	Diam. (in.)	Diamond Pyramid Hardness	Composition Weight (%) C	Mn	P	S	Si	Cr	Ni	Mo	Fe	Al	Cu	Others
Iron-nickel chromium alloy (1)*	A286	1 3/4	327	0.06	1.65	0.024	0.01	0.57	15.60	25.61	1.26	Bal.	0.15	-	1.90 Ti, 0.004 B
		1/4	284	0.033	1.51	0.026	0.009	0.61	15.66	24.58	1.25	Bal.	0.20	-	2.72 Ti, 0.003 B
Alloy steel (2)	4340	1/4	423	0.40	0.73	0.007	0.018	0.30	0.78	1.78	0.25	Bal.	-	-	
Martensitic stainless steel (3)	440C	1 3/4	658	1.04	0.41	0.016	0.07	0.41	16.75	0.11	0.56	Bal.	-	-	
		1/4	618	0.96	0.34	0.016	0.013	0.44	17.57	0.25	0.51	Bal.	-	0.10	
Copper-base alloy	Aluminum bronze ASTM-B-169-55-F	1 3/4	187	-	-	0.01	-	0.09	-	-	-	0.66	7.96	Bal.	
Aluminum-base alloy (4)	2024T4 QQ-A-268-1	1 3/4	149	-	0.60	-	-	0.25	0.10	-	-	0.25	Bal.	4.35	1.50 Mg, 0.25 Zn
	AMS-4120-E	1/8	166	-	0.58	-	-	0.23	0.10	-	-	0.22	Bal.	4.38	1.52 Mg, 0.23 Zn
Nickel	"A"-Nickel	3/4	321	0.04	0.22	-	0.008	0.02	-	99.5	-	0.13	-	0.09	
Copper	Oxygen-free high conductivity	1 3/4	95	-	-	-	-	-	-	-	-	-	-	99.95	
Aluminum	Electrical grade	1 3/4	35	-	-	-	-	-	-	-	-	-	99.45		
Silver	Fine, Grade A	1 3/4	71	-	-	-	-	-	-	-	-	-	-	-	99.95 Ag
Tungsten	-	1/8	283	-	-	-	-	-	-	-	-	0.006	-	0.0021	99.9 + W, 0.0016 Mg, <0.0001 Ca
Aluminum oxide	Synthetic-sapphire	1/8	2520	Polycrystalline rod											
Tungsten carbide	Flame plate	-	1440	Flame sprayed on A286. Specified thickness 0.005 inch											
Polytetrafluoro-ethylene	AMS 3651	3/16	-	Commercial rod											
Polytetrafluoro-ethylene	AMS 3651	1 3/4	-	Reinforced with 15% glass fiber. Impregnated with 5% molybdenum disulfide											
Gold plating	-	-	-	Plated on A286 in accordance with MIL-G-14548A to a minimum thickness of 0.0005 inch											
Silver plating	-	-	-	Plated on A286 in accordance with CQ-S-365 Type II to a minimum thickness of 0.0005 inch											
Molybdenum disulfide	No. 4306	-	-	Phenolic bonded on A286											
Grease	ETR-II	-	-	Silicone oil with organic dye thickener.											

*Specified heat treatment: (1) 1300°F, 1 hour, oil quench; 1325°F, 16 hours, air cool. (2) 1550°F, 1/2 hour, oil quench; 1000°F, 1 hour, air cool. (3) 1850°F, 1/2 hour, oil quench; 450°F, 2 hours, air cool. (4) 920°F, 1/2 hour, water quench; 375°F, 9 hours, air cool.

Table XIII. Summary of Ranger 1 Passes from Which Friction Data Were Obtained 24 August 1961[114]

Greenwich Mean Time	Orbit Number	Altitude (km)	Vacuum (mg Hg)[9]
0528	13	163	2.6×10^{-6}
0658	14	162	2.6×10^{-6}
0705	14	179	1.7×10^{-6}
0834	15	170	2.1×10^{-6}
0842	15	219	6.7×10^{-7}
0915	16	443	1.7×10^{-8}
1007	16	181	1.6×10^{-6}
1017	16	260	3.0×10^{-7}
1049	17	453	1.5×10^{-8}
1145	17	230	5.2×10^{-7}
1226	18	427	2.1×10^{-8}
1401	19	378	4.3×10^{-8}

Of the materials tested under space conditions, polytetrafluoroetheylene (PTFE) sliding against metals and ceramics, as well as metals sliding on metals with a molybdenum disulfide lubricant, had low coefficients of friction averaging 0.04. Ceramics sliding against unlubricated metals and metals with grease or gold-plate lubrication had intermediate average coefficients of friction near 0.13. Unlubricated metals sliding on metals showed moderately high coefficients of friction averaging 0.5, but some metal couples had coefficients of friction in excess of 1.0. There was a general trend toward low coefficients of friction with metals having a high hardness. This trend is in agreement with that observed by other investigators. In addition, the coefficients of friction were usually higher for metals having a high material solubility.

A coefficient of friction experiment was also programmed for the Ranger 2 flight. However, a malfunction in the second stage of the space vehicle occurred and Ranger 2 was injected into a low-altitude orbit. Only a very limited amount of friction data was received from the spacecraft, and it was insufficient to be analyzed and was not included in this report.

2. ORS Cold Welding and Friction Experiments

A series of cold welding and friction experiments in the space environment are being conducted by the Air Force Rocket Propulsion Laboratory. According to a trade publication, the first of these

Table XIV. Coefficients of Friction for Materials Tested in the Space and Terrestrial Environments[114]

Rider	Disk	Lubricant	In Air; Preflight Assembly No. 4; 15 to 30 Min.*	In Lab; Vacuum Assembly No. 4; 50 to 100 Min.	In Space; Ranger 1 Assembly No. 4; 800 to 1300 Min.	Literature Data Friction Coefficient, In Vacuum
Nickel	Copper	None	0.20	0.67 0.22 & 1.12 **	0.56 0.42 & 1.0 **	1.50 after 10^1 to 10^2 turns
Aluminum	Copper	None	0.23	0.94	0.66	
Silver	Copper	None	0.38	0.22	0.70	
Tungsten	Copper	None	0.34	0.16	0.40	0.41 after 10^1 to 10^2 turns
Iron alloy A286	Iron alloy A286	None	0.26	0.50	0.62	
Copper alloy	Copper alloy	None	0.28	0.73	0.43	For brass: 0.60 to 0.75 after 10^3 strokes
Aluminum alloy 2024	Aluminum alloy 2024	None	0.56	0.67	0.33	0.32 to 0.57 after 10^3 strokes
Steel 440C	Steel 440C	None	0.07	0.18	0.10	0.44 after 10^5 turns
Iron alloy A286	Copper alloy	None	0.32	0.53	0.44	
Aluminum alloy 2024	Iron alloy A286	None	0.23	0.32	0.27	
Steel 4340	Iron alloy A286	None	0.33	0.38	0.60	
Steel 440C	Tungsten carbide	None	0.20	0.16	0.18	
Aluminum Oxide	Steel 440C	None	0.11	0.16	0.07	0.36 after 10^5 turns
PTFE ****	Iron alloy A286	None	0.02	0.04	0.02	
PTFE	Aluminum alloy 2024	None	0.02	0.06	0.08	
PTFE	Tungsten carbide	None	0.03	0.05	0.02	
Steel 440C	PTFE glass fiber	Molybdenum disulfide	0.04	0.05	0.05	
Aluminum alloy 2024		Impregnated in disk	0.01	0.07	0.01	
Iron alloy A286	Iron alloy A286	Phenolic	0.14	0.09	0.03	For 440C on 440C, phenolic-MoS_2: 0.025 after 10^5 turns
Steel 4340	Iron alloy A286	Bonded molybdenum	0.17	0.08	0.07	For MoS_2 pellet on stainless: 0.06 to 0.10 after 4×10^3 turns
Aluminum alloy 2024	Iron alloy A286	Disulfide	0.09	0.14	0.02	
Copper alloy	Iron alloy A286	On disk	0.15	0.09	0.01	
Iron alloy A286	Iron alloy A286	Silver plate on disk	0.25	0.17	0.46	For 440C: 0.06 after 10^5 turns
Iron alloy A286	Iron alloy A286	Gold plate on disk	0.12	0.17	0.13	For 440C: 0.10 after 10^5 turns
Iron alloy A286	Iron alloy A286	Grease	0.16***	0.20	0.24***	
Steel 4340	Iron alloy A286	Grease	0.08	0.24	0.05	
Copper alloy	Iron alloy A286	Grease	0.12***	0.17	0.14	
Aluminum alloy 2024	Iron alloy A286	Grease	0.15	0.11	0.11	

*At 3 rpm, nominal.
**Average for low-friction and high-friction modes, respectively.
***Data were discarded for one rider to which lubricant was apparently not properly applied.
****Polytetrafluoroethylene.

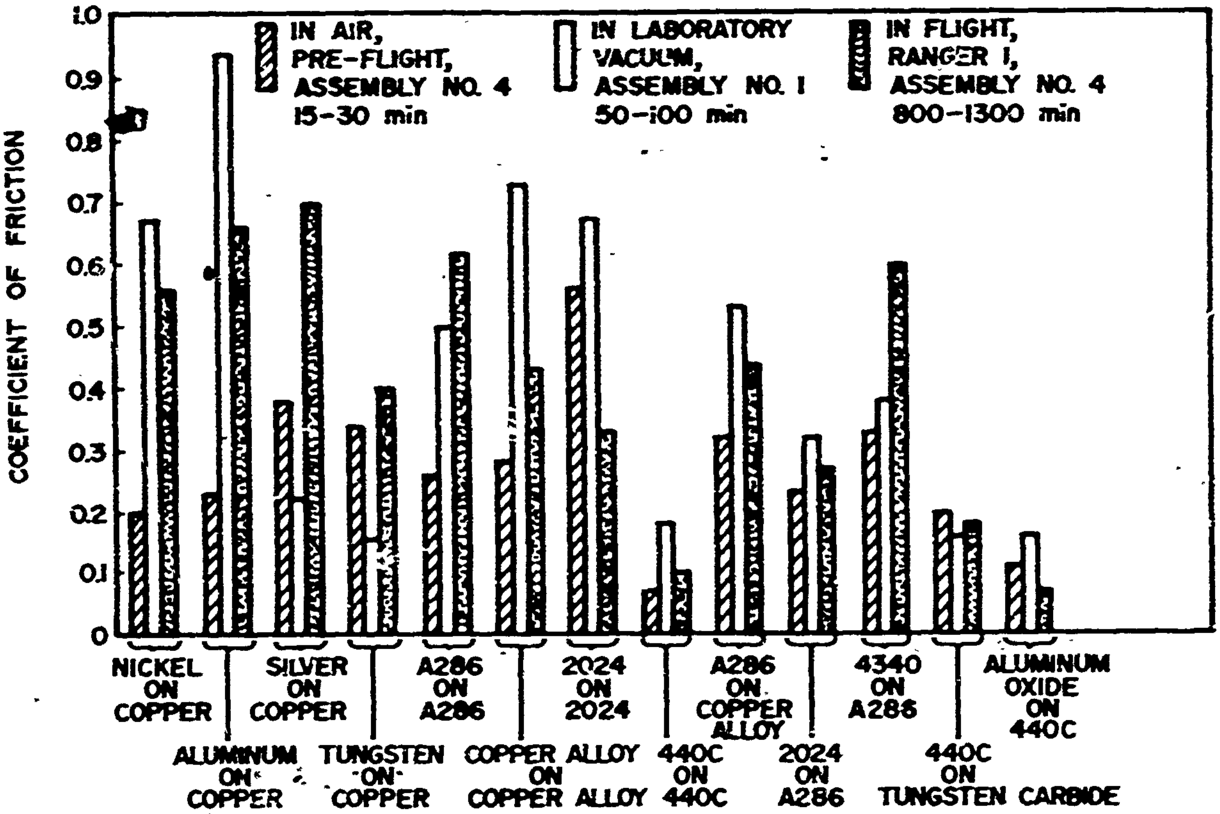


Figure 43. Coefficients of Friction for Unlubricated Metallic and Ceramic Materials[114]

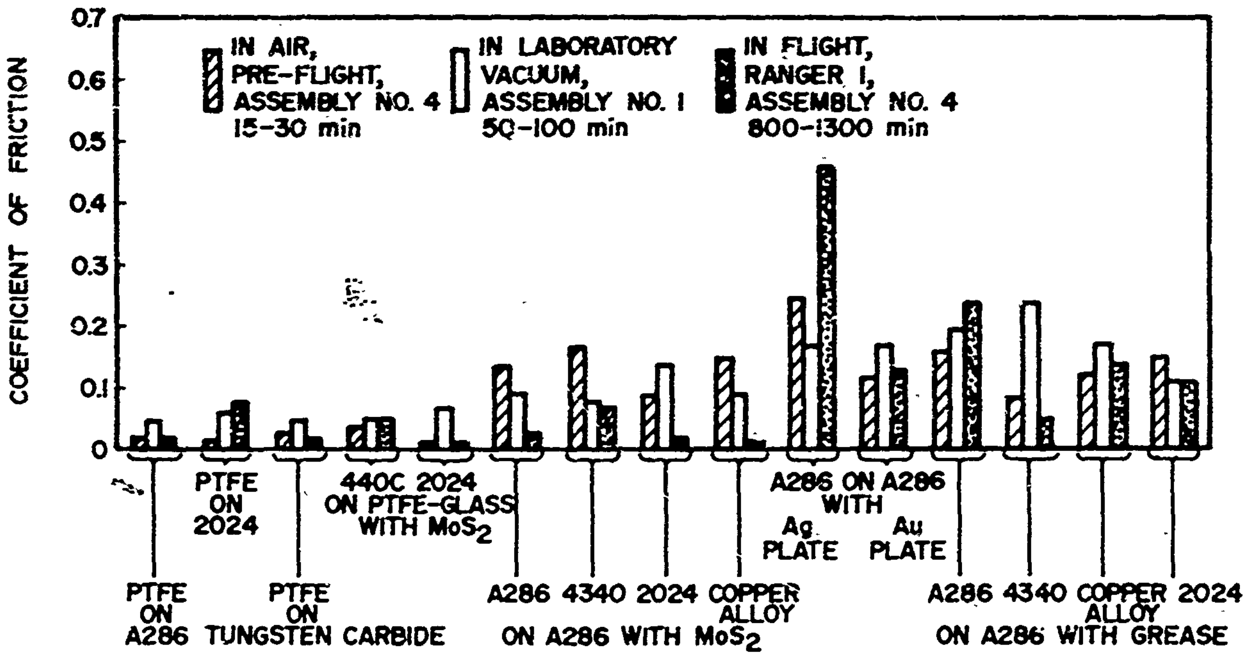


Figure 44. Coefficients of Friction for Lubricated and Polymeric Materials[114]

experiments (ORS-2) was scheduled for flight in May 1966. This research satellite contained equipment for five cold welding experiments.[115] The second satellite, designated ORS-3, is scheduled for flight in December 1966 and contains equipment for a number of friction experiments. The octahedral research satellites (ORS) have been designed and constructed by TRW Systems.

a. Cold Welding Experiments

Laboratory tests in ultrahigh vacuum have shown that cold welding between atomically clean metal surfaces can occur when the surfaces are cleaned in a vacuum. However, such data do not provide a definite answer to the question, "will significant cold welding occur under actual service conditions?" The ORS cold welding experiment was designed to answer this question by acquiring data in the space environment.[116, 117] These data could also be used for a cross-comparison of space flight results with laboratory testing results.

With the ORS-2 satellite, five cold welding experiments can be incorporated and flown in a single satellite. Four valves, actuated by solenoids, can be used to evaluate four material combinations that serve as the valve seat and poppet. The fifth solenoid actuator can be used to open and close eight metal-to-metal contacts. The adhesion and friction properties of the materials to be evaluated by in-flight tests were determined during an earlier program sponsored by the Air Force Rocket Propulsion Laboratory at the National Research Corporation.[87] Figure 45 shows the material combinations incorporated in the flight experiments.

The valve experiments, V_1 - V_4, will be accomplished with four solenoid valves in which different materials are used for the valve seat and poppet (Figure 46). The body of the valve has been modified to permit maximum exposure of the test surface the vacuum of outer space; however, the surfaces are self-shielded from radiation. Each of the valve experiments will be cycled periodically from a normally closed position over a period of about six months. The frequency of actuation will result in about 50,000 cycles for each valve. Since it is known that the presence of contaminants has an important bearing on adhesion, equipment will be incorporated in each valve to produce camphor vapor during the first 30 days of flight. Then, the supply of the contaminant vapor will be shut off, and the valve will continue to operate in the normal space vacuum for the remaining five months of the flight. The valve actuation and the occurrence of cold welding will be detected by monitoring the solenoid coil current.

MATERIAL	440C	17-4PH	WC	2014-0 Al	OFHC Cu
440C S. S.	X	V_1	V_2	S_1	S_8
17-4PH S. S.		S_5	V_3	S_7	S_6
TUNGSTEN CARBIDE (WC)			V_4 S_4	X	X
2014-0 Al				S_3	X
OFHC Cu					S_2

EXPERIMENT DESIGNATION

VALVE EXPERIMENTS (NORMALLY CLOSED)

V_1 440C x 17-4PH

V_2 440C x WC

V_3 17-4PH x WC

V_4 WC x WC

SUPPLEMENTAL CONTACT EXPERIMENTS (NORMALLY OPEN)

S_1 440C x 2014-0

S_2 OFHC x OFHC

S_3 2014-0 x 2014-0

S_4 WC x WC

S_5 17-4PH x 17-4PH

S_6 17-4PH x OFHC

S_7 17-4PH x 2014-0

S_8 440C x OFHC

MATERIAL CALLOUTS

1. 440C QQ-S-763 Rc 55-60
2. 17-4PH AMS 5643 H-900
3. WC CARBALLOY TYPE 44A
4. OFHC Cu QQC 502
5. 2014-0 Al QQ-A-266

Figure 45. Contacting Materials and Experiment Designations[117]

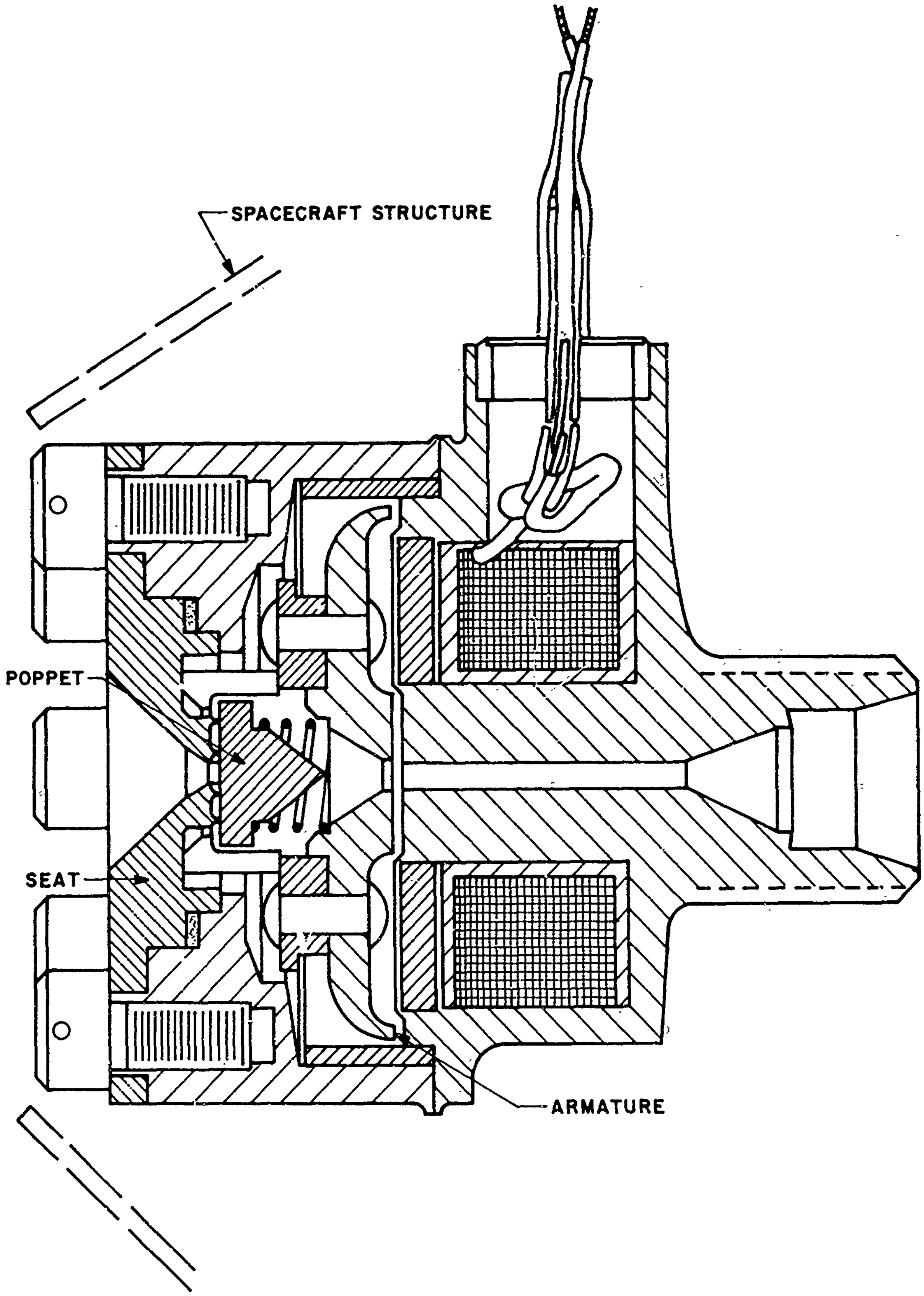


Figure 46. Cross-Section Sketch of the ORS-2 Valve Fxperiment (Scale 4X)[117]

The fifth experiment, designated $S_1 - S_8$, will use the same solenoid actuator mechanism that was used on the valve experiments. However, the unit was modified to permit the closure of eight normally open contacts as shown in Figure 47. The geometry of the contactor experiments and its satellite mounting was designed to expose the contacts to the effects of solar radiation and the vacuum of outer space. When the solenoid is energized, the eight contacts are closed and the occurrence of cold welding will be detected by the increase in time required for opening the contacts. The contacts will close and open approximately 400,000 times during the six-month test cycle.

The valve mechanism that will be used for both types of cold welding experiments was selected following an extensive testing program.[118] During these tests, six commerically available solenoid valves were evaluated on the basis of the following tests:

1) Life.
2) Leakage rate between seat and poppet.
3) Vibration.
4) Actuation time.
5) Pull-in voltage.
6) Thermal shock.

Following the selection of materials, one contactor experiment and two valve experiments were tested in a vaccum of 10^{-6} to 10^{-7} torr by the Air Force Rocket Propulsion Laboratory.[119] Each valve unit was actuated 96,000 times and the contactor was actuated 768,000 times. No evidence of adhesion or cold welding was observed during these tests. Four calibrated valve experiments and one contactor experiment were further tested by the National Research Corporation.[120] Before actuation, the experiments were thermal-vacuum conditioned at 200°F in a vacuum of 10^{-8} torr for three days. After cooling to ambient temperature, the pressure was reduced to 10^{-12} torr for testing. Over a period of 57 hours, the valve experiments were subjected to 64,980 cycles of opening and closing and no evidence of adhesion was noted. The contactor experiment was cycled 482,480 times during the test period, again no evidence of adhesion was observed.

The tests under simulated conditions indicated that adhesion between the selected material combinations should not be a problem. However, these data must be verified by the in-flight tests in a circular orbit having an altitude of 2000 nautical miles.

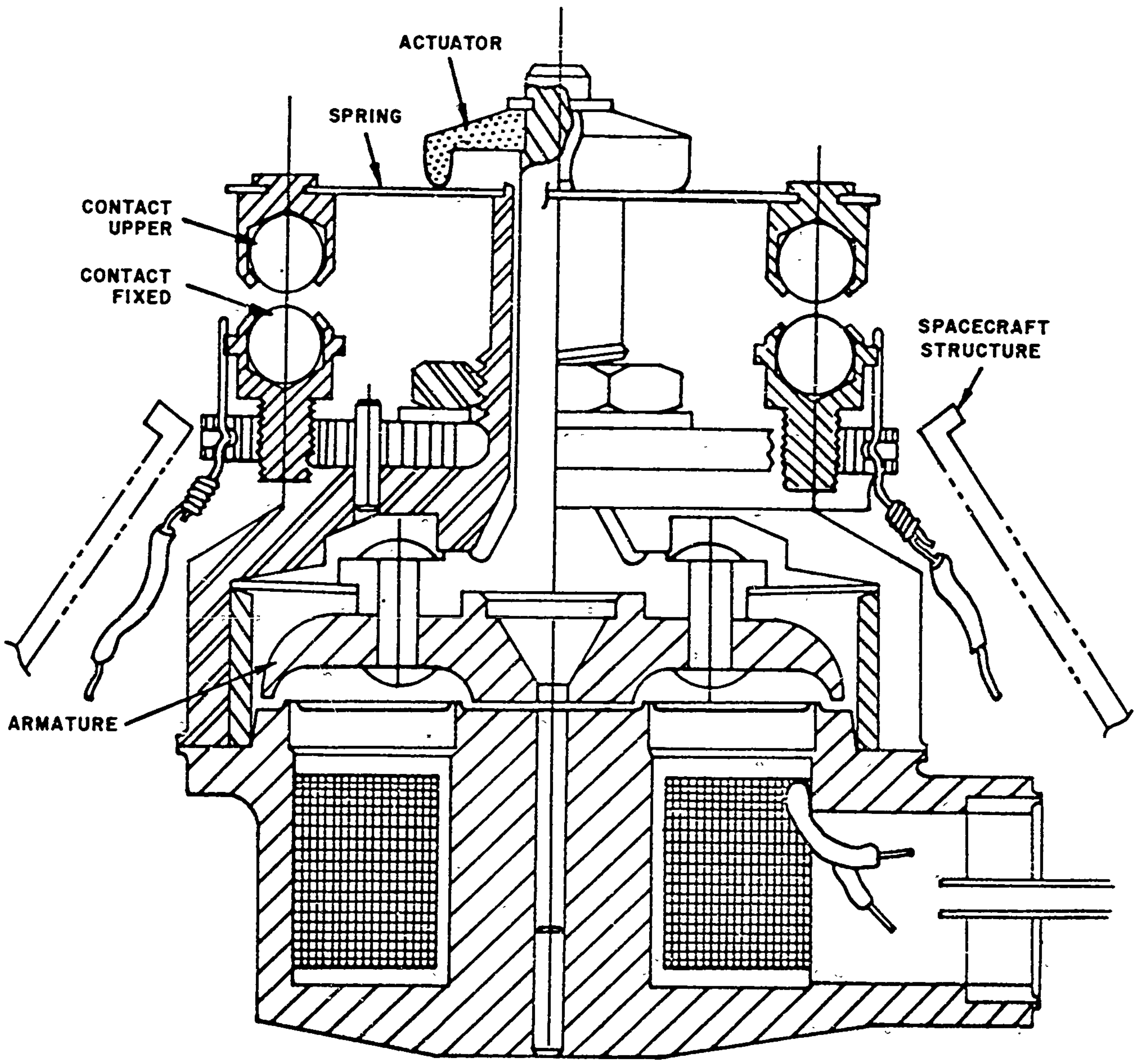


Figure 47. Cross-Section Sketch of the ORS-2 Supplemental Contact Experiment (Scale 4X)[117]

b. Friction Experiments

Friction experiments will be carried on the ORS-3 research satellite that will be launched into an orbit having an apogee of 60,000 nautical miles and a perigee of 4000 nautical miles. Frictional surface operating in the space environment is affected by the sublimation and evaporation of lubricant films or residual contaminant films. If the surfaces became sufficiently clean, the frictional forces may increase due to metal-to-metal adhesion on a microscopic scale. Experimental evidence shows that the coefficient of friction increases when sliding surfaces are in contact in an ultrahigh vacuum. There are numerous propulsion system functions where friction can be encountered such as in valves, linkages, gears, etc. Therefore, a friction experiment was designed for the ORS-3 satellite. Its main objective was to measure the change in the coefficients of friction for a number of metal-to-metal, metal-to-dry film, and self-lubricating combinations during long-time exposure in the space environment. It is planned to use these data to calibrate a vacuum test chamber, so more meaningful data can be obtained in future laboratory studies.

The preliminary design of the friction experiment has been completed.[121, 122] The equipment was designed in a modular method so that identical friction modules could be placed in a laboratory vacuum chamber and in the ORS-3 research satellite. In this way, a direct comparison of laboratory data and data obtained in the space environment could be made. It is planned to install two such modules (eight friction couples per module) in the spacecraft.

The experimental configuration produces sliding motion between 16 different pairs of frictional surfaces. A sliding or reciprocating motion was selected over rotary motion because a range of sliding velocities could be readily investigated, and all surfaces except those being tested could be sealed. The flexure arm assembly is shown in Figure 48. This assembly includes strain gages to measure the frictional drag and the force that is applied normal to the test specimen surfaces. Provisions are made so the normal force can be adjusted to a selected valve. An overload release is also provided to prevent stoppage of the module drive mechanism in case of seizure of the test specimens. The eight reciprocating flexure arm assemblies are driven by a direct-current motor. The equipment design lifetime was based on a six-months active period; however, this could be shortened or lengthened. The frequency of sliding was selected as one cycle per 10 seconds.

A laboratory model of the friction experiment module was designed and constructed. Its performance was evaluated in air, and the

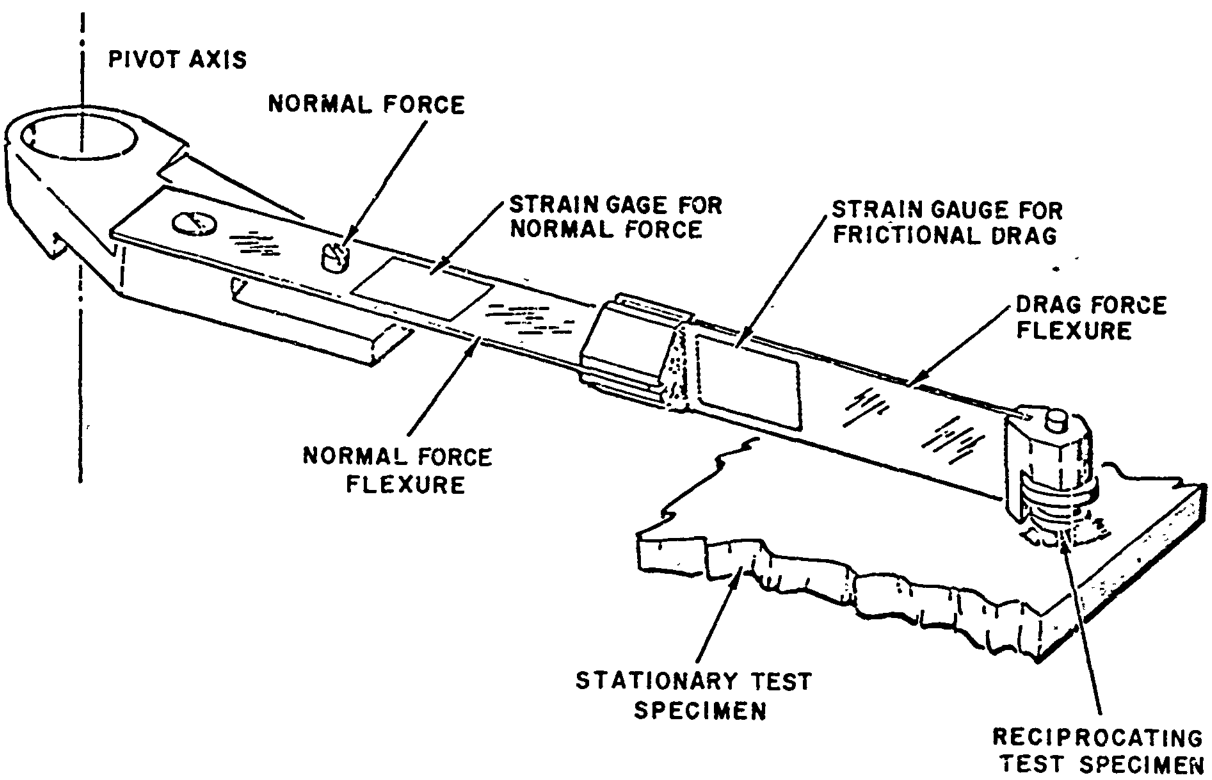


Figure 48. Flexure Arm Assembly for Friction Experiment[121]

coefficients of friction were determined for such material combinations as tungsten carbide to 17-7 PH stainless steel, 2014-T6 aluminum alloy to 6061-T6 aluminum alloy, 17-7 PH stainless steel to 440 C stainless steel, and 17-7 PH stainless steel to mild steel.

Additional design verification and development testing will be performed before the design is finalized. The materials to be tested have not been selected yet, but it is expected that sixteen material combinations will be chosen from the following four groups:

1) Engineering alloys.
2) Elemental metals.
3) Self-lubricating solids.
4) Thin films or solid film coatings.

3. Other Experiments

Undoubtedly, other experiments on adhesion and friction phenomena in the space environment are in the planning study. For example, MSFC is planning to study the positive and negative aspects of cold welding in the near future. During a manned space flight it is planned to remove a printed circuit board from an assembly, and effect a repair on the circuit board. Adhesion or cold welding should not prevent removal of th circuit board from the connector, yet this same phenomenon may be useful in repairing a defective component or connection.

Section VI. CONCLUSIONS

There is an abundance of information on the adhesion or cold welding of metals in a vacuum simulating the conditions of outer space; however, there is little direct correlation between these data because of the manner in which they were acquired. This is understandable, because the objectives of research programs vary from fundamental studies on adhesion and friction to the development of lubricants for a specific application. Also, there is a complete lack of standardization in the selection of a test specimen, the method of surface preparation, and the test procedures. This situation is analogous to those existing in other areas of space research. It has been reported that the thermal properties of surfaces in the space environment varied as much as 10 to 30 percent from the data acquired in a simulated space environment. Even more discouraging was the lack of correlation between data obtained by different organizations. It has been recommended that data on the thermal properties of solids be accompanied by a complete description of the surface; i.e., the surface preparation, surface roughness, presence of films, etc. Similarly, some degree of standardization in the methods of acquiring data on adhesion phenomena is desirable but unlikely, because there are disagreements regarding the basic nature of adhesion and the relative importance of the variables that influence adhesion.

There are numerous methods to acquire data on adhesion and friction. Aside from the physical geometry of the specimen, its surface condition, and the test environment, the occurrence of adhesion is influenced greatly by the magnitude and type of loading. For example, at Syracuse University adhesion is being studied by touch-contact procedures. At Hughes Aircraft Company, National Research Corporation, and others, appreciable loads are applied in determining the static adhesion properties of materials. Other organizations are investigating the dynamic adhesion properties of materials with widely varying contact loads and types of motion. Thus, the lack of correlation between adhesion and friction data is hardly surprising.

As discussed below, there is substantial agreement on several aspects of adhesion:

1) Surface Contaminants - Regardless of the exact nature of the mechanism that causes adhesion, the presence of oxides and films of adsorbed gases on metal surfaces prevents metal-to-metal contact and minimizes adhesion.

2) Motion - There is uniform agreement that adhesion is promoted by the relative movement of the contacting surfaces. Such movements remove surface contaminants and increase the real area of contact.

3) Environment - All of the experimental evidence indicates that adhesion is more likely to occur in a vacuum than under standard atmospheric conditions. There is the possibility that contaminants can be removed from surfaces by evaporation or dissociation in a vacuum. Even more important is the slowness with which surface contaminants reform in a vacuum once they are removed. The occurrence of adhesion is minimized at low temperatures. Elevated temperatures promote diffusion between the melting surfaces and relax the stresses induced by deformation processes.

4) Material Properties - While there is general agreement that the occurrence of adhesion is related to the physical and mechanical properties of materials, there are few instances where enough supporting data have been acquired to relate adhesion to a specific material property. The experimental data indicate that adhesion is minimized when the contact materials have a high hardness, high elastic modulus, and low ductility.

5) Loading - Contact loads promote adhesion by increasing the real area of contact between the mating surfaces.

1. Prevention of Adhesion

On the basis of current knowledge, several suggestions on minimizing or preventing adhesion between metal surfaces can be discussed. As mentioned briefly above, metals having a high hardness, high elastic modulus, and low ductility should be used for contact surfaces. The adhesion between such materials is weak, because the real area of contact is minimized; also, it is presumed that bonds between the surface asperities fracture when the load is removed and elastic stresses become effective. Contact loads near the yield stress of the material should be avoided. Loads which cause plastic deformation are deceptively low, because the real area of contact is a small fraction of the apparent area of contact. To minimize adhesion, the ambient temperature should not exceed one-half of the absolute melting temperature of the contact materials. High temperatures can promote adhesion by relieving stresses and increasing diffusion processes. Obviously,

sliding motion between contacting surfaces should be minimized wherever possible, because of its effect on surface oxides and films. To further minimize adhesion, the use of wear- and vacuum-resistant surface films and lubricants should be considered.

While there is general agreement on the effectiveness of the above measures in reducing or preventing adhesion, the measures in the following paragraphs are subject to discussion and warrant further investigation.

a. Dissimilar Metals

Some difficulty in obtaining significant adhesion between mutually insoluble metals has been experienced, but investigations have shown that mutually soluble metals and most partially soluble metals can be bonded readily. However, the use of dissimilar metal couples to minimize adhesion should be approached with caution, since some mutually insoluble metals have been successfully roll bonded. In addition, significant adhesion between certain of such metals has been observed in an ultrahigh vacuum by Keller and Johnson[62] and Golego.[97]

b. Crystal Lattice Structure

There is considerable evidence that metals with a hexagonal crystal lattice structure do not bond as easily as metals with a cubic lattice structure. Research with certain rare-earth metals which have a hexagonal structure at room temperature showed that the coefficients of friction for these metals increased significantly when they transformed to a cubic structure at elevated temperatures.[72] Sikorski[34, 35] has also accumulated considerable evidence to show that metals with a cubic crystal lattice structure bond more easily than those with a hexagonal structure.

c. Atomic Volume and Diameter

Sikorski[34] has shown that the coefficient of adhesion generally increases with the atomic volume. The effect of atomic diameter on adhesion has also been investigated by Golego[97] who showed that the coefficient of friction was particularly low when the contacting metals had widely different atomic diameters.

2. Promotion of Adhesion

In general, the positive aspects of adhesion, i.e., the tendency for contacting materials to bond, can be emphasized by reversing the

recommendations for minimizing adhesion. Thus, to enhance adhesion, the following should be used:

1) Metals having low hardness, low elastic moduli, and high ductility.
2) High ambient temperatures.
3) Ultrahigh vacuum conditions.
4) Sliding motion between contact surfaces.
5) Unlubricated surfaces.

In addition, mutually soluble metals should be used as contact materials, and the use of metals with a cubic crystal lattice structure should be considered.

3. Electrical Connections in a Space Environment

Adhesion phenomena can significantly influence the behavior and performance of electrical contacts and connections in the space environment. Certain electrical components such as switches, potentiometers, and connectors depend on sliding motion to ensure good contact between mating surfaces. Thus, one of the major prerequisites for promoting adhesion is fulfilled by the operating characteristics of such components. Sliding motion also produces wear particles which may promote additional adhesion and are a potential source of noise in low-level electrical circuits. It is evident that a sound understanding of adhesion processes is necessary for the successful operation of electrical components in the space environment.

The use of the measures suggested for minimizing or preventing adhesion is encouraged to prevent seizure of electrical contacts in space. However, trade-offs in the selection of contacting materials will be needed. For example, molybdenum is a hard metal that has a high modulus of elasticity and limited ductility. From the standpoint of preventing adhesion, molybdenum is an excellent choice as a contact material, but it is a relatively poor conductor of electricity. The resistivity of molybdenum is about 5.2 microhm-centimeter while that of silver is only 1.58 microhm-centimeter. On the other hand, silver will cold weld readily in an ultrahigh vacuum. However, small quantities of molybdenum as a constituent in a dry film lubricant have been incorporated in a silver-copper-molybdenum disulfide contact material for slip-ring brushes with good results. Thus, the benefits associated with the superior lubricating properties of molybdenum have been realized, while retaining the high-conductivity properties associated with silver and copper. The use of gold or silver thin films as lubricants

to prevent adhesion has been accomplished with some success. Current cold welding and friction experiments in the space environment should be followed closely to determine the likelihood of seizure of potential electrical contact materials.

Measures to promote adhesion have also been suggested, but they may not be directly applicable to the repair of electrical connections and components in the space environment. Special tools whose design is based on cold welding principles will be useful for such applications. However, the following use of certain commercially available equipment and procedures should be considered also:

1) A miniaturized version of the "wire wrap" equipment developed by the Bell Telephone Laboratories may be useful in joining wires or making wire-to-terminal joints. Metal-to-metal adhesion occurs in the terrestial environment as a result of the wrapping process. Stronger adhesion forces should be experienced in the space environment.
2) The thermo-compression bonding method developed by Christensen and Anderson[123] may also be useful in space joining operations. Fine wires have been attached to semiconductor chips at moderate temperatures and pressures by these procedures. The mechanism of bonding is primarily adhesion. In a variation of this joining method called twist-compression bonding, shear stresses produced by twisting the wire against a metallized substrate promote adhesion at ambient temperature.
3) Work is currently underway to develop exothermic joining processes that can be used in the space environment.[124] While these studies are directed toward brazing operations that are conducted at relatively high temperatures (approximately 1100° to 1800°F), the existence of a self-contained heat source that can be used in space is significant. Since a moderate increase in temperature promotes adhesion, small exothermic heat sources may be useful in repair operations.
4) Simple repairs in electrical circuitry may be possible by removing surface contaminants by abrasion, so that metal-to-metal contact between mating surfaces can be achieved.

Section VII. RECOMMENDATIONS

As mentioned in earlier sections of this report, there is an abundance of information on the adhesion of metals exposed under conditions that simulate the vacuum of outer space. However, there is little correlation between the data because of the diverse methods of data acquisition used by organizations active in this area of research. To realize the full benefits of this information, it is recommended that the data from all sources be assembled and analyzed to establish agreement for coefficients of adhesion and friction for various metal combinations. It is expected that considerable agreement already exists for elemental metal samples; understandably, there is much less agreement for couples involving complex structural alloys. The data relating adhesion to the physical and mechanical properties of the metals should also be analyzed.

Once agreement between the adhesion data is established, the information can be used as a basis to predict the behavior of materials in the space environment.

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13. ABSTRACT

~~This~~ report presents a comprehensive literature survey of adhesion bonding (cold welding) in the space environment. Space characteristics are summarized and experimental methods for reproducing these conditions are investigated. Information is particularly directed towards electronics and the metals used for electrical contacts. A total of 124 references are cited along with a selected bibliography of 44 citations.

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